CRANFIELD UNIVERSITY

TOM STORR

THE EFFECT OF COVER CROPS ON SOIL QUALITY INDICATORS IN A CEREAL AND SALAD ROTATION

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD
Academic Year: 2016 - 2019

Supervisor: DR JACQUELINE HANNAM
Associate Supervisor: DR ROBERT SIMMONS
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ABSTRACT

Cover crop (CC)s influence soil function and thus affect crop yield and ecosystem services provided by soil. CCs are a relatively new soil management practice in U.K. agriculture, but are gaining in popularity amongst farmers. However, research on the effect of CCs on soil function in the short term and how to manage CCs effectively in the U.K. is limited.

Therefore, field trials investigated the effect of CCs on physical (visual evaluation of soil structure, penetration resistance, bulk density, soil shear strength and soil moisture), chemical (total organic carbon and soil available nitrogen) and biological (earthworm abundance, microbial biomass and diversity) soil quality indicators, as well as crop yield. CCs were established between wheat and forage maize. A companion crop established with the maize remained overwinter after maize harvest until lettuce establishment the following spring. CCs placed between wheat and maize only affected available soil nitrogen with limited significant effects on other soil quality indicators. The addition of a companion crop significantly improved earthworm abundance, microbial community diversity and biomarkers associated with fungi. The companion crop significantly reduced bulk density and soil shear strength at 0.05 and 0.15m, respectively as well as penetrative resistance at 0-0.03m depth. Thus, continued plant presence, achieved through the establishment of cover and companion crops in the rotation allows for the accumulation of positive effects on soil quality and function in a short period of time (20months).

Additionally, a survey distributed to U.K. farmers (n = 117) provided an understanding of the use, management and challenges associated with CCs. Respondents reported that the Basic Payment Scheme supporting CC use is not suitable and could be more flexible. Additionally, it took >3 years to realise benefits to soil structure. The knowledge gained from the survey can be used to inform future research and policy so that CCs can be implemented effectively to benefit the ecosystem services provided to the farmer and wider community

Keywords: Field trial, Survey

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LIST OF ABBREVIATIONS

AHDB	Agriculture and Horticulture Development Board
ANOVA	analysis of variance
AMF	arbuscular mycorrhizal fungi
BD	bulk density
C	carbon
CC	cover crop
CpC	companion crop
DEFRA	Department for Environment, Food and Rural Affairs
Est	Establishment
FAME	fatty acid methyl ester
FS	frost sensitive
ha	hectare
Kg	kilogram
l	litre
m	metre
MBC	microbial biomass carbon
N	nitrogen
NS	not significant
P	phosphorus
PLFA	phospholipid fatty acid
PRG	perennial rye grass
s	second
SEM	standard error of the mean
SOC	soil organic carbon
S(OM)	soil (organic matter)
TF	tall fescue
TOC	total organic carbon
VESS	visual evaluation of soil structure
WH	winter hardy
Yr	year
YT	yellow trefoil

1 SOIL AND COVER CROPS

1.1 Soil and Agriculture

Sustainable intensification in agriculture is the production of crops to meet the food and fibre needs of a growing world population (expected to reach ≈10 billion in 2050) whilst minimising the environmental impact (United Nations, 2017). Since World War II, agriculture has focused on increasing production to feed the growing world population, but this has relied on the use of manufactured fertiliser, crop protection products and mechanisation (Pingali, 2012). Land is required to produce 95% of the food resources for the world population, however, 33% of this land globally is classified as having high or moderate soil degradation (FAO, 2015, 2011). Soil degradation, 'the change in soil health status resulting in diminished capacity of the ecosystem to provide goods and services for its beneficiaries' encompasses many different types of degradation (FAO, 2018). The main soil threats in Europe have been identified as: soil contamination, soil salinization and acidification, soil nutrient depletion, compaction, loss of structural stability, declining soil organic matter, changes to soil biodiversity and soil erosion via wind and water (Virto et al., 2015). Individual countries are not faced with the same threats to soil. Soil erosion, soil compaction and organic matter loss are the greatest threat to soils in England, and cost the economy £150-£200m a year (DEFRA, 2009a, 2011b).

Soil degradation/threats are directly linked to the loss of function of the soil. Soil function, though difficult to define, encompasses numerous 'tasks we ask of the soil' and the extent to which a given soil achieves these tasks or services is dependent on its inherent properties (texture) and properties that may be altered by management (bulk density, pH etc) (Gregory et al., 2015; Hatfield et al., 2017). Typically soil function describes: habitat provision, nutrient cycling, decomposition, soil structure, water cycling and organic matter cycling, which deliver the ecosystem services provided by the soil (Bünemann et al., 2018). Soils, through their aforementioned functions provide a complex and interconnected network of goods and services to human kind: i) provisions – food, water, fibre and fuel, ii) regulatory – gas, water, climate, floods, erosion, pollination and disease, iii) cultural – aesthetic, education and recreation, and iv) support – habitat and biodiversity (Adhikari & Hartemink, 2016; Millenium Ecosystem Assessment, 2005). Historically, the main service valued by humanity has been the production of food and fibre - though the practices utilised to achieve this has been to the detriment of other services provided by soil, resulting in biodiversity loss (Pennings et al., 2005), soil erosion (Holz et al., 2015) and carbon emissions (Evans et al., 2016). Agriculture and forestry are responsible for food and fibre production but the land management under these systems is also responsible for the majority of the threats to soil (van Lynden, 2000). It is not only the wider environment affected by poor ecosystem services; in the U.K. agricultural yields have been plateauing since the mid 1990's, with some of this attributed to soil compaction and loss of organic matter (Knight et al., 2012). Agriculture, therefore, has its own incentives to improve soil management (increased yields and profit) but also future policy may reward farmers for public goods e.g. erosion control, water quality, biodiversity (Downing & Coe, 2018).

Through the use of alternative soil management practices, it may be possible for agriculture to halt or reverse the threats to soil and improve the functioning of the soil and the ecosystem services provided. Soil degradation in other parts of the world (e.g. Dust bowl in America during the 1930's) led to the development of principles that help to protect soils (Farooq & Siddique, 2015). The three principles i) minimimal tillage ii) permanent soil cover and iii) crop rotation are collectively known as conservation agriculture (Farooq & Siddique, 2015). In the UK, these principles are increasingly applied to arable and combinable crop rotations where no-tillage can be utilised in combination with cover crop (CC)s. However, in horticulture implementing these principles are particularly difficult, as soils are often intensively cultivated for the year round production of high value salad and vegetable crops.

Horticultural production is based on soils that that have particular characteristics favourable to crop management. The Fens, located in East Anglia are fertile, stoneless and friable Histosols where the water table can be manipulated, resulting in 89% of the area been classified as Grade 1 or 2 Agricultural Land (Keymer & Brayshaw, 2012). The improved workability and ability to manipulate soil water means that vegetable crops can be better controlled to meet supermarket requirements. In these soils, crops can be harvest throughout the year with relative ease compared to clay soils. The Fens produce 37% of England's vegetables and are important to national food security and employment. The food and manufacturing industry in the Fens employs 17,500 people and is worth £1.7bn (Keymer & Brayshaw, 2012).

In addition to food security, the Fens are a vital carbon (C) store. The lowland Fens store 57% on England's soil carbon (Natural England, 2010). However, intensive use of the lowland peat Fen soils for salad and vegetable production has led to severely degraded soils that are a great source of carbon emissions compared to other land uses (Evans et al., 2016). The Histosols of the Fenland, were originally drained in the mid 16th century using wind power to lower the water table. Over 200 years later, steam engines allowed the permanent drainage of the area for agriculture. Oxidation, resulting from the drainage and subsequent cultivation of the Fens has promoted the loss of C from the soils leading to increased CO_2 emissions. It is estimated that cultivated soils release an equilavent of 25-28t CO_2 ha yr^{-1} whilst undisturbed fen soil is a CO_2 sink (Evans et al., 2016). Shrinkage and agricultural machinery traffic has increased the bulk density of the soils and further reduced soil depth (Gauci, 2008).

Recent assessment, shows that the Histosols in the Fens have reached the most decomposed state (Sapric) and in places the sapric Histosol horizon is only 0.4m in depth, below which lies estuarine clay (Hannam et al., 2014). This means that many areas of former Histosols are now reclassified to Mollic Gleysols. The current rate of soil loss is estimated at 0.015 -0.02m per annum due to oxidation, shrinkage and wind erosion, giving an estimated remaining horticultural lifespan of 25 – 50 years (Holman, 2009; Keymer & Brayshaw, 2012).

A change to practising conservation agriculture in the Fens is necessary to slow down the soil degradation caused by the heavy traffic and frequent tillage (whilst the fens are drained and used for intensive vegetable and salad production it is unlikely that the loss of soil C will be stabilised or reversed). Use of zero-till would not be possible in a horticultural rotation but providing continued plant cover through the use of CCs can be achieved. CCs are non-harvested crops that are established between cash crops. The ability of CCs to improve soil productivity was recognised by the Chou Dynasty and Roman Empires (North Carolina Agricultural and Technical State University, n.d.; Meisinger et al., 1991) and is still relevant today. The benefits of CCs arise through i) growth of aboveground biomass and ii) growth of root systems. It is the accumulation of biomass and growth of the root systems that impart subtle changes to the soil that through improved soil function can affect soil ecosystem services.

Improvement of soil functions and/or soil ecosystem services can be measured using soil quality indicators. Soil quality is 'the capacity of the soil to function within the ecosystem and land use boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health' (Doran & Parkin, 1994) is assessed using a suite of soil quality indicators for the physical, chemical and biological components of soil (Doran & Safley, 1997). A specific indicator is used to measure the effect of a soil management practice/ change to one or several of the soil functions. There are many soil quality indicators that may be used but they must i) influence the soil function for which the assessment is being made, ii) is measurable against a definable standard and iii) sensitive to change in time and space (Karlen et al., 1997). Thus, using specific soil quality indicators it is possible to quantify the effect of a certain soil management practice, such as the use of cover crops, on soil quality. Often this is used to imply how a soil management decision may affect an environmental ecosystem service or crop yield. For example the measurement of total organic carbon (a soil quality indicator) is affected by the addition of organic matter (e.g. CCs) and is primarily associated with the decomposition and organic matter cycling functions of the soil, this can then be used to infer effects on climate regulation (ecosystem services).

The following review focuses on the effects of CCs to the following soil functions and services:

Soil structure – measured via bulk density, soil penetration resistance and the visual evaluation of soil structure (VESS).

Water cycling – measured through soil moisture content and infiltration.

Organic matter – measured through the accumulation of SOC

Nutrient cycling – measured by the availability of nitrogen

Soil biodiversity – measured via earthworm population, microbial and fungal biomass and their community composition.

Production - crop yield

These indicators are widely used in published research but may also be accessible to the agricultural industry/farmers. This is important as future agricultural policy may require farmers to monitor their soils beyond the current requirements of soil nutrient content. Where possible the references are from research in the U.K. but this is limited, so references are also made to overseas research that has relevance to U.K. agricultural and environmental conditions.

1.2 Soil Physical Indicators

CCs, through the activity of their roots can improve the continuous macropores and pore organisation of the soil when compared to treatments without CCs (Abdollahi et al., 2014; Carof et al., 2007). The term ‘biodrilling’ was proposed by Creswell and Kirkegaard (1995) to describe the tillage effect that roots can have on soil structure (Elkins, 1985). Biodrilling refers to the root channels left behind from decaying roots, which provide a pathway of least resistance in the soil profile. The biopores created allow the following crop’s roots to access the resources in the subsoil (Kautz et al., 2013). Plant species with tap roots are more suited to penetrating compact soil layers as the large diameter roots are least likely to buckle or be deflected, creating biopores >2mm in diameter (Chen & Weil, 2010; Han et al., 2015b; Materechera et al., 1992). Additionally fluctuations in root diameter, linked to plant transpiration, may help to loosen the soil surrounding the root (Hamza et al., 2001). Radish species, with a large tap are capable of structural remediation, creating biopores and alleviating the effects of soil compaction (Abdollahi et al., 2014; Burr-hersey et al., 2017; Chen & Weil, 2011). Additionally, studies report that CCs with a fibrous root architecture (red fescue and black oats) can also penetrate a compacted soil layer and result in soil porosity changes (Burr-hersey et al., 2017; Carof et al., 2007). Fibrous roots, have a greater root length density and root surface area when compared to tap roots as the roots are finer and more numerous. Finer roots, encountering a compacted soil layer are able to utilise smaller pores and with a greater number of roots they also have an increased exploratory potential than tap roots (Clark et al., 2003). Thus, fibrous roots can penetrate compacted soil layers with a greater number of roots, alleviating the effect of soil compaction through additional biopore creation (Burr-hersey et al., 2017) and improved macro-aggregation - also associated with fibrous roots (Bronick & Lal, 2005).

Soil in close proximity to the plant roots can be subject to plant root exudates that help to aggregate and bind soil particles (Kirkegaard et al., 2008) allowing the biopores to become more stable (Kautz et al., 2013). Increased dilute acid-extractable polysaccharides, partially originated from CCs are well correlated with the mean weight diameter of the soil aggregates following CC treatments (Liu et al., 2005). CC roots, like all roots are able to physically bind and re-align soil particles (Bronick & Lal, 2005). Through these mechanisms roots can help prevent seedbed slumping (Chan & Heenan, 1996) and stabilise soil structure due to better aggregation (Carof et al., 2007; Hermawan & Bomke, 1997).

1.2.1 Soil structure

Soil structure can be assessed using numerous visual evaluation techniques that require differing levels of expertise (Emmet-Booth et al., 2016). The methods can be quick and easy to complete and require little equipment - often just a spade. With training and experience, visual evaluation techniques correlate well with other physical soil quality methods and provide a semi-quantitative assessment of soil structure (Guimarães et al., 2011, 2013; Johannes et al., 2017). Other measurements such as bulk density and soil resistance to penetration give quantitative information on soil compaction. Bulk density measurements quantify the unit mass per unit volume of soil particles and pore space available for water and air transport (Hamza & Anderson, 2005). Soil resistance to penetration gives an estimate of resistance to growth experienced by plant roots (Bengough & Mullins, 1990).

Visual assessment of soil can be conducted to compare the effect of treatments or general soil condition. The visual evaluation of soil structure (VESS) (Ball et al., 2007; Guimarães et al., 2011) and the visual soil assessment (Shepherd, 2003) have previously been used in the U.K.. Comparing over winter stubble to autumn sown CCs in the UK Stobart *et al.,*(2015) found that there is approximately a 0.5 point improvement in the VESS score in the following Spring. Munkholm *et al.,*(2013) report that a diverse rotation including a clover CC resulted in a lower Sq score (better soil quality) for VESS in a no till situation. Their findings also indicate that VESS is linearly correlated to air filled porosity and is positively influenced by soil macropore complexity. However, other studies suggest that VESS is not sensitive enough to differentiate between rotational effects (Abdollahi & Munkholm, 2014; Askari et al., 2013).

Quantifiable changes to soil structure following CCs may take up to 4 years to become apparent (Çerçioğlu et al., 2006; Jokela et al., 2009). After 2 years of trials using CCs no significant differences to bulk density were measured (Chen & Weil, 2011; Sánchez de Cima et al., 2015). This may be due to the growing roots pushing soil particles horizontally, thus having little effect on the gross bulk density of the soil (Chen & Weil, 2011). There is evidence for small reductions in bulk density following short term experiments (Hubbard et al., 2013; Haruna & Nkongolo, 2015). After 5 years of fodder radish growth penetrative resistance was reduced (1.62 Mpa) when compared to no CC (1.85 Mpa) at 0.32-0.38m depth, suggesting that the CC can alleviate soil compaction (Abdollahi & Munkholm, 2014). A meta-analysis of experiments in the Argentina Pampas revealed that reductions in bulk density following CCs were small (1% at 0-0.2m depth) but did occur in 63% of cases at 0 -0.05 or 0.06m depth and 49% of cases at 0-0.02m depth (Alvarez et al., 2017). Alvarez *et al.,*(2017) reported that changes to soil penetration resistance decreased by 15-20% at 0-0.1 and 0.1 -0.2m depths following CCs when compared to a fallow.

The majority of research presented above has been conducted outside of the U.K. – mainly in the Americas. These studies have taken place on sandy or silty loam soils, with some clayey soil trial sites included in the Pampas meta-analysis (Alvarez et al., 2017). Literature relating to the U.K. is very sparse – Stobart *et al.*,(2015) provide the only published (conference proceedings) research on the effect of CCs on soil structure in a field trial situation. However, it is likely that the numerous trial sites used in this research were based on mineral soils in combinable crop rotations. Burr-Hersey *et al.*,(2017) present research obtained from pot trials and whilst insightful into the root growth characteristics of CC species, the natural structure of the soil was lost through sieving the soil and therefore not representative of U.K. field conditions.

The lack of research conducted in the U.K. investigating the effect of CCs on soil structure is evident by the little published research available. Furthermore, all of the literature cited relates to trials conducted on mineral soils and thus may not be applicable to the lowland Fen soils (Drainic Sapric Histosol). The lowland Fen soils have a high organic matter content (>25 % w/w) compared to the mineral soils of the locations used in the cited literature. Additionally, the crop rotations used in the literature are dominated by combinable crops that require less intensive soil cultivation than horticultural rotations.

1.2.2 Soil Water Dynamics

CCs are able to influence water infiltration (movement of water into the soil), drainage (movement of water through the soil profile) and soil water balance through their amendment of the physical soil structure and transpiration. CCs reduce soil strength at the soil surface (Folorunso et al., 1992) and may also leave 'large open root channels' (Chen & Weil, 2011). These effects are favourable to increase water infiltration (Stobart & Morris, 2014; Jakab et al., 2017; Blanco-Canqui et al., 2011). Previous tillage practices can affect water infiltration where existing plough plans can prevent CCs from improving the infiltration rate (Abdollahi et al., 2014). Prior to tillage, water infiltration was greater in an organic system following CCs compared to no CCs (Sánchez de Cima et al., 2015). Blanco-Canqui *et al.,*(2017) suggest that CCs should be utilised to improve soil hydraulic properties in zero till practices, otherwise one could not expect longer term benefits from zero till when compared to conventional tillage.

Whilst CCs may permit a greater infiltration of water into the soil there are concerns that CCs deplete the water resources for the following crop reducing yield, especially in low rainfall (< 500mm per annum) regions (Nielsen et al., 2016). Research also reports that CC treatments compared to treatments without CCs can reduce soil water availability prior to cash crop establishment in regions of greater rainfall (exceeding >600mm per year) (Basche et al., 2016; Krstić et al., 2018). However, Basche *et al.*,(2016) concluded that due to replenishment by rainfall, soil water in the CC treatments had returned to the same level as the no CC treatments by the day of cash crop establishment in 5 of the 7 study years. It is estimated that in the U.K., water use by CCs is 20mm t^{-1} of dry matter though in the warmer climate of France this may double to

40mm t^{-1} of dry matter (Allison et al., 1998a). CC species differ in their use of water; vetch and phacelia have a greater transpiration efficiency (biomass production per unit of transpired water) than rye or mustard in the semi-arid (< 500mm yr) conditions of Austria (Bodner et al., 2007). Although the study still considered mustard to be a water efficient crop because the majority of the water is lost to transpiration and not evaporation from the soil surface. Research, in Serbia (610mm annual rainfall) reports that triticale reduced soil water to a greater extent than vetch (Cúpina et al., 2017). Despite differences between CC species, a mixture of CCs does not use water any differently to a single species CC – both of which on average use 1.78x more water than a fallow treatment (Nielsen et al., 2015a).

Soil water is also manipulated by the termination method of CC. Conducting field studies in Poland, Harasim *et al.*,(2016), report that prior to cash crop establishment a ploughed bare soil fallow had a significantly greater soil water content than white mustard, both of which were greater still than the oilseed rape or winter rye that was mown and desiccated. In a no-till rotation, which possibly explains the contradictory findings, White and Weil (2010) reported that the mulch provided by a rye CC increased soil water content at 0.2m depth when compared to no CC and no till. Termination date is also critical to the soil water balance following CCs as earlier termination reduces the competition for water between the CC and cash crop, especially in dry climates or periods of low rainfall (Alonso-Ayuso et al., 2018). Depending on the species established, termination date can be determined by the weather as winter killed CC species will senesce below a certain temperature (frosts). Following field trials in Vancouver, Canada, Odhiambo and Bomke (2007), reported that soil moisture was not any different following winter killed spring barley compared to winter wheat and rye.

The effect of CCs on soil moisture is climate specific and dependent on CC management. Furthermore, within a climate zone unexpected weather patterns year to year can alter the effect of CCs on soil water. In a dry year, soil water reduction by a CC can be more extreme than during a year of normal and evenly distributed rainfall (Krstić et al., 2018). In the U.K., rainfall is highly variable between the major crop production regions: east of England (500mm) and North East England (>1000mm) (Met Office, 2016). Studies from other areas with similar annual rainfall to the East of England indicate that CCs reduced soil water prior to the cash crop (Krstić et al., 2018; Nielsen et al., 2016). Whilst a long term study conducted in a Iowa with greater annual rainfall and similar to that of the Midlands or North East England reported soil water use by CCs is replenished by the rainfall (Basche et al., 2016). However, in regions of greater rainfall (>1000mm), CCs may result in the soils remaining wet and thus problematic for cash crop establishment (White & Weil, 2010). It has been suggested that CCs can be utilised to dry out heavy land in the U.K. (Shah et al., 2015), however the research above would suggest that this would not be due to CCs *per se* but rather their management. To ensure that there is not a negative effect on the following cash crop due to CCs, suitable CC termination timing and residue management will be vital, which will depend on region and anticipated weather. There remains the knowledge gap for identifying the balance of CC management (termination timing) within a given agro-climatic region to ensure the risk to the following cash crop by either too little or too much water is reduced

1.3 Soil Chemical Indicators

Chemical indicators have traditionally been the main indicator used to measure soil quality. Farmers periodically test the nutrient status of their soils and apply nutrients, in particular nitrogen (N), but other elements too (phosphorus, potassium, sulphur etc) for crop growth. In addition to the nutrients required for crop growth, soil organic matter (soil organic carbon) is of primary importance too; soil organic matter serves a vital role in the regulation and availability of water and soil nutrients (Baldock & Nelson, 2000). Furthermore, the accumulation of soil organic matter and the sequestration of carbon in soils – the largest store of carbon in the world – can of help offset carbon emissions (Lal et al., 2015). Recently, soil organic matter and nutrient levels of soil have been ranked as the No. 1 and 2 key indicators, respectively, for measuring soil health (Soil Security Programme, 2016).

1.3.1 Nitrogen

In most ecosystems plant growth is limited by the availability of nitrogen (N) and phosphorus (P) (Güsewell, 2004). CCs are able to manipulate the availability of plant nutrients in the soil (Eichler-Löbermann et al., 2008). During CC growth, under favourable conditions, CCs can scavenge 120 kg N ha^{-1} and 30 kg P ha^{-1} in only 3 months (Wendling et al., 2016). Alternatively, legume CCs (and other legume plants) can form symbiotic relationships with *Rhizobium,* which are able to fix N_2 from the atmosphere into organic N (Follett, 2001; Pandey et al., 2017; Tonitto et al., 2006). This mechanism of nitrogen fixation can be limited by temperature, soil moisture extremes and pH as well as other environmental conditions (Peoples et al., 1995). Following senescence of the CC, the availability of the organic nitrogen within the CC biomass, whether scavenged or fixed biologically, is dependent on the C:N ratio. Net immobilization of N occurs at a C:N ratio ≥ 26 and mineralization occurs at a ratio <13 (Justes et al., 2009). C:N ratio is dependent on species and maturity, with each CC or mixture having a unique C:N ratio. Legume CC species have a low C:N ratio due to high accumulation of N content and low tissue C thus, leading to a greater supply of N from decomposition (Di Palo & Fornara, 2015; White et al., 2017)

Nitrogen export from agricultural practices is a major contributor to ground and surface water pollution (Braakhekke et al., 2017). Bare soils, without a cash crop are prone to leaching and surface water run-off; CCs can be establish to eliminate bare soils and are an important method to reduce to the leaching of nitrates (Plaza-Bonilla et al., 2015). Following harvest, winter CCs can accumulate 20-60kg N ha^{-1} and substantially reduce nitrate leaching by 40-70% compared to an overwinter fallow (Tonitto et al., 2006). In England, the average N concentration in drainage reduced from 24 to 11 mg l^{-1} when CCs were used compared to bare soils (Shepherd, 1999). In particular it has been shown that non-legume species (oilseed radish, mustard, cereal rye) in America (Dozier et al., 2017), France (Couëdel et al., 2018), Scotland (Baggs et al., 2000), Ireland (Hooker et al., 2008) and England (Cooper et al., 2017; Macdonald et al., 2005; Shepherd & Lord, 1996) are effective at reducing nitrate leaching. Baggs *et al*., (2000) reports that naturally regenerated vegetation (weeds/ volunteers) is also effective at N uptake. Effective nitrate leaching control from CCs may be comprised if sowing of the CC is late, (Teixeira et al., 2016) or if a winter killed CC is used (White et al., 2017). A shorter growing period (Kaspar et al., 2012) and decomposition in early spring of the winter killed CC could be less effective at preventing N leaching compared to an over-winter CC (Dean & Weil, 2009; Silgram & Harrison, 1998). However, this depends on the winter/ spring rainfall which dictates the end of the drainage period and therefore the risk of N leaching. It is possible that CC decomposition in early spring could benefit N supply to the following cash crops without posing a considerable risk to N leaching.

The balance of N supply and N leaching regulated by a CC can be difficult to manage as it is dependent on CC species chosen, winter/ spring rainfall and the sowing date of the following crop. For dry regions of the U.K., where cumulative drainage is small, there is concern that CCs may lead to 'pre-emptive competition' for N and so reducing the supply to the following cash crop and negatively affecting yield (Macdonald et al., 2005). In other temperate regions, it has been shown that rye and rye grass CCs reduce available N at the time of sowing the cash crop, whilst legume CC species are able to increase the N service (Couëdel et al., 2018; Thorup-Kristensen, 2001b). The use of a crucifer and legume CC mixture increased N mineralisation due to the decreased C:N ratio compared to a sole crucifer CC (Couëdel et al., 2018).

Given the concern of pre-emptive competition for N due to CCs, especially in low rainfall areas, such as the East of England there is a need to investigate CC management strategies that may reduce the competition for N and subsequently negatively affect the following cash crops growth.

1.3.2 Soil Organic Matter (SOM) and Soil Organic Carbon (SOC)

SOM influences the biological, chemical and physical properties of the soil and is considered to be one of the most important constituents of soil with both quality and quantity vital to soil structure and fertility (Ding et al., 2006). The loss of SOM and failure to replace it after crop harvest has increased the difficulty of plant production (Abawi & Widmer, 2000). Tillage exposes the protected C to microbes and accelerates mineralization and production of carbon dioxide, thus leading to carbon losses (Evans et al., 2016; Sánchez de Cima et al., 2015) Tillage, also affects the placement and accumulation of OM within the soil profile, with stratification of OM occurring in no till systems (Abdollahi & Munkholm, 2014; Moore et al., 2014).

CCs are one mechanism to increase OM input into soils, including in tillage based agricultural practices (Plaza-Bonilla et al., 2016). Belowground inputs make a greater disproportional contribution to SOM due to their persistence and physical entrapment in rhizodeposits compared to aboveground biomass that is readily consumed (Bodner et al., 2010; Gale & Cambardella, 2000; Mazzilli et al., 2015; Tiemann & Grandy, 2015). Meta-analysis, predominately using studies from mineral soils, of the effect of CCs on SOC report an annual increase of 320-490kg C ha^{-1} yr^{-1} (Poeplau & Don, 2015; Ruis & Blanco-Canqui, 2017).

Increases of soil OC or OM following CCs have been reported by a number of studies (Ding et al., 2006; Frasier et al., 2016; Harasim et al., 2016) on light sandy soils over a trial periods ranging from 3 years to 10 years. Mazzoncini *et al.,*(2011) reported that legume CCs increased SOC compared to non-legumes or a control after 5 and 15 years following trial establishment. Studies also report that SOC was not significantly increased by the use of CCs over 3 or more years (Abdollahi & Munkholm, 2014; Beehler et al., 2017; Mathew et al., 2012; Sánchez de Cima et al., 2015; Shepherd, 1999). Kaspar *et al.,*(2006) report that spatial variability and a relatively high inherent SOC content (e.g. in non-sandy soils) can make the small changes to SOC arising from CC use hard to measure over a short trial period.

All of the above studies, have been conducted on low OM soils and where an increase in SOC (OM) is reported the inherent SOM content of those soils is <2%. Again, the meta-analyses conducted were dominated by mineral soils with only one study exceeding an SOC content of 2% (≈3.5% SOM). The research of the effect of CCs on SOM has been conducted on soils that have an inherently very low SOM content when compared to the Fens of Cambridgeshire. The soils of the Fens have a high SOC content which can exceed 20.5% (Hollis et al., 2015). It is likely that the high OM content of these soils will make it extremely hard to detect the small changes resulting from the carbon addition of the CCs, especially over the short term (Kaspar et al., 2006). Nevertheless, there is a lack of research investigating the effect of CCs on soil organic matter/ carbon in soils with an inherently high organic matter content.

1.4 Soil Biological Indicators

Biological soil quality indicators have previously been overlooked in favour of physical or chemical soil quality indicators, despite the fact that soil biological indicators are considered the most responsive to differences in the soil environment (Bünemann et al., 2018). Earthworms are important soil engineers and promote soil fertility through burrowing activity and cast production (Shipitalo & Korucu, 2016). Bacteria and fungi are responsible for the decomposition of plant material, nutrient cycling and aggregation (Brady, 1984; Bronick & Lal, 2005; Gregory et al., 2007). The microbial degradation of plant material and their own necromass contribute to the non-living part of SOM (Miltner et al., 2012).

1.4.1 Earthworms

Despite CCs increasing organic matter supply into agro-ecosystems and theoretically beneficial to earthworms (Bertrand et al., 2015) only a few studies reported a significantly increased earthworm population (Korucu et al., 2018; Reeleder et al., 2006) or biomass (Roarty et al., 2017) following CCs. Other studies in the U.K. and Ireland report that CCs generally increased earthworm population (Overthrow & Brookes, 2007; Roarty et al., 2017; Stobart et al., 2015). Following CCs, studies in Estonia (Sánchez de Cima et al., 2015), the U.K. (Stroud et al., 2017) and the United States (Ashworth et al., 2017) reported no significant difference to earthworm abundance when compared to a control without CCs.

Several reasons exist why CCs may not improve earthworm abundance. Tillage is known to reduce earthworm abundance (Curry et al., 2002) and may be used to incorporate CCs or is utilised throughout the rotation for crop establishment. Generally, where tillage is used in the rotation earthworm abundance is reduced compared to no till or conservation agriculture practices (Perego et al., 2019; Crotty et al., 2016). The life cycle of L. *terrestris* is 6 months under favourable conditions (Butt, 1993) so studies may not allow enough time for earthworms to complete their lifecycle before counting population differences following CC treatments. Additionally, non- CC plant species such as volunteer crop growth and weeds (present in control plots) can also provide a food source to earthworms (Ashworth et al., 2017). Finally, it is proposed by Stroud *et al*., (2017) that the crop residues used by earthworms expose them to the agrochemicals used in crop and CC management – though further work needs to be completed to establish if agrochemicals (when applied at typical field rates) affect earthworm abundance.

Several studies on earthworm population following CCs have been completed in England (Overthrow & Brookes, 2007; Stobart et al., 2015; Stroud et al., 2017) and one in Ireland (Roarty et al., 2017). Of the journal published studies (Roarty et al., 2017; Stroud et al., 2017) only single species CC were used and therefore a knowledge gap exists to research the effect of a mixed species CC on earthworm abundance. It is vital to understand the effect of a mixed species CC given that this is the practice of many farmers in U.K., and further encouraged by Basic Payment Scheme only allowing a mixture of CCs too (Rural Payments Agency, 2016). Furthermore, it has been shown that earthworm abundance and biomass is greater following a single species legume CC (pea) than brassica CCs (mustard, radish, oilseed rape), and so a mixture may balance out the more positive effects of one CC species over another (Roarty et al., 2017).

1.4.2 Microbial Community

Studies report that CCs increase microbial biomass of the soil when compared to a no CC control (Finney et al., 2017a; McDaniel et al., 2014; Tejada et al., 2008) and within 3 years of their implementation, under favourable conditions and no-till systems the carry capacity of the soil may be reached (Frasier et al., 2016). The increase and/or diversity of organic matter, resulting from the use of CCs, is linked to microbial activity (Jokela et al., 2009; Tejada et al., 2008). In addition to organic matter and residue addition, living roots from the CC, provide exudates into the rhizosphere which also support microbial activity. The microbial community is sensitive to the presence of these roots as fatty acid methyl ester concentration, an indicator on microbial presence, reduced in the period between CC termination and wheat establishment (Calderón et al., 2016). CCs influence the spatial organisation of the soil community, with generalist bacteria concentrated in the top soil and specialist bacteria more prevalent at 0.1-0.3m depth and below the plough layer (Alahmad et al., 2018).

CCs, owing to their unique chemical composition have species specific effects on the microbial community. The physical root traits of the CC affect the soil microbial community as tap-rooted species increase microbial activity at depth relative to other CC species with shallower root architecture (Calderón et al., 2016). In the United States, Finney *et al.,*(2017a) report that cereal rye and oats increase the presence of arbuscular mycorrhizal fungi (AMF) whilst the legumes (hairy vetch and red clover) increased non-AMF. In Spain it has also been reported that legume CCs (vetch) did not increase the presence of AMF when compared to barley (García-González et al., 2018). Other studies, in the United States, have also reported that cereal CCs (rye and oats) support AMF colonisation (Kabir & Koide, 2002; White & Weil, 2010). In contradiction to Finney *et al.,*(2017a) and García-González (2018) it is reported, following a meta-analysis using studies from 5 continents, that AMF colonisation has a strong response to legume CCs compared to non-legume species (Bowles et al., 2017). Brassicas do not form AMF associations as the residues produce isothiocyanates that have a bio-fumigation effect on the soil (Angus et al., 1994; Borek et al., 1995; Smith et al., 2004; Njeru et al., 2014). However, this may not affect the AMF root colonisation (White & Weil, 2010) or the growth (Higo et al., 2018) on the following maize crop.

With the exception of Calderón (2016) who compared a 10 species CC mixture to several single species CC in a very dry climate (≈300mm rainfall between April –December) and Alahmad *et al,*(2018) who in a plough based system compared a CC mixture to no CC the majority of the research uses single species CCs. Despite using mixtures these studies were conducted under experimental conditions that differ in both the cultivation strategy and climate of the East England. Cultivation strategy implemented in CC farming systems also affects soil microbial community as no till increases bacterial numbers overall but there abundance decreases with depth (Schmidt et al., 2018). Reduced tillage also promotes extensive fungal hyphal networks that leads to greater fungi:bacteria ratio as the soil environment is more favourable to fungal growth (Six et al., 2006).

1.5 Crop Yield

Crop yield is the measurement of biomass production. Easily measured at scale by the farming community and also from trial sites, it provides an overview of the effect of a particular soil management change on crop production but not how specific soil functions may have been affected. As well as soil management, crop yield is also affected by weather, crop variety, agronomic programmes, pests and disease.

A meta-analysis using studies conducted throughout the United States and Canada, reported that crop yield was improved by 21 and 13% following legume CCs and mixed species CCs, respectively, when compared to no CC; grass species CCs had no effect on maize yield (Marcillo & Miguez, 2017). Another meta-analysis, which included 7 trials from European studies reported a 3% decrease in crop yield following non-legume CCs (Tonitto et al., 2006). Both meta-analyses report that in an organic or reduced N farming systems, legumes have a greater benefit to crop yield (Marcillo & Miguez, 2017; Tonitto et al., 2006). Other studies report that CCs: increased (DuPont et al., 2009; Kramberger et al., 2009; Chen & Weil, 2011) or had no effect on maize yield (Gabriel & Quemada, 2011; Dozier et al., 2017). In dry climates (<350mm rainfall in the wheat growing season) it was reported that CCs due to soil water use, reduced wheat yield by 10%, regardless of whether a single or mixed species CC is grown (Nielsen et al., 2016). Reduced maize yield following CCs has also been reported in the temperate climate of Serbia (Krstić et al., 2018). The use of CCs compared to bare soils in a plough based system maintained yields of different cash crops in both North and Southwestern France (Alahmad et al., 2018; Plaza-Bonilla et al., 2016). A recent meta-analysis reported that CCs produced the greatest yield response in maize crops followed by soybean and cereal crops (Hallama et al., 2018).

In the U.K. CCs have had variable effects on the yield of different crops: i) no effect on sugar beet yield (Allison et al., 1998b; Shepherd, 1999), ii) increased spring barley (Shah et al., 2015) and ware potato (Shepherd, 1999) yield and iii) reduced oilseed rape yield (Stobart & Morris, 2015).

Crop yield can be affected by several CC management decisions. Firstly, the decision to establish CCs of similar species to the cash crop may have a negative effect on crop yield (Barel et al., 2017) and may be the reason for reduce oilseed rape yield following brassica CCs (Stobart & Morris, 2015). CC termination date also influences crop yield. CCs terminated up to 6 days before maize establishment in the United States increased yield by 30% compared to CCs terminated more than 2 weeks prior to cash crop establishment that reduced yield by 3% (Marcillo & Miguez, 2017). Finally, CCs may have a greater yield benefit in reduced tillage (Marcillo & Miguez, 2017) or N agricultural systems (Tonitto et al., 2006). Thus, in addition to the main drivers of cash crop yield (agro-climate, weather, pest and disease), CC management decisions (CC species chosen and termination date) within a given agricultural system (tillage intensity and N use) all to some extent influence the magnitude of the effect CCs have on cash crop yield.

1.6 Conclusion

The literature review highlighted some general trends in the effect of CCs on the soil physical, chemical and biological indicators that can inform further research. There is little effect of CCs on soil physical quality indicators and earthworm abundances when measured after one CC season. Measuring changes to soil physical quality indicators requires the accumulation of biopores – dependent on root growth and earthworm activity. Measuring differences in earthworm population, is dependent on the reproductive cycle of the species and may be up to 6 months long in favourable soil conditions. The time required for differences to soil quality indicators to be measured following the implementation of CCs will require the design or use trials where CC establishment has been maximised. In short-term projects, (e.g. 3 year PhD) located on new trial sites this will require several phases of CCs to be implemented sequentially within a suitable rotation. Alternatively, long term trial sites with CCs grown throughout the rotation would allow for sampling to take place immediately.

Over short timescales, within the growing season, CCs can affect soil moisture and available nitrogen with differences monitored during and after CC growth. These soil quality indicators are sensitive to CC management decisions such as termination and species selection, as well as local weather conditions. Previous research has focused on the potential of CCs to reduce N leaching from the soil profile, and so there is a lack of knowledge regarding N dynamics during CC growth and N availability to the following cash crop (White et al., 2016).

CCs are a growing trend in U.K. agriculture but currently there is little scientific research on the effect, use and management of CCs in a U.K. context. This is evidenced by the small number of studies in the UK and/or Ireland concerning the effect of CCs on earthworms (Roarty et al., 2017; Stroud et al., 2017), soil N management (Allison et al., 1998b,a; Baggs et al., 2000; Cooper et al., 2017; Macdonald et al., 2005; Shepherd, 1999; Shepherd & Lord, 1996), soil structure (Stobart et al., 2015) and yield (Stobart & Morris, 2015). The agricultural industry is also lacking in the understanding of CCs in the U.K., which is summed up in the following quote, ‘a bewildering array of CCs are being marketed to cure a range of ills, including poor soil structure, resistant weeds, nutrient leaching and soil pests … often backed by impressive claims that are lacking in hard facts…with very little quantified data available’ (Agrovista, 2016).

With a few exceptions the majority of the CC research has been conducted outside of the U.K. and Ireland. Most of the research was produced in America, which has a very different climate to the U.K. Even within the U.K., the climate, particularly rainfall can vary considerably between the arable region of the East of England and the North West. Climate affects the cash crop species chosen for a rotation and thus the time of year in which a CC is grown. Climate, also, affects the CC species chosen and their vigour, which subsequently, affects root and aboveground biomass production and therefore biopore formation or organic matter return. Secondly, the trials reported in the literature were established on mineral soils, which are distinctly different to the organic Histosol soils of the Fens. The Fens, due to their high fertility have rotations dominated by salad and vegetable crops that require intensive soil cultivation practices. Most rotations in the reviewed literature contained combinable crops that may be established and/or harvested with very minimal soil disturbance or trafficking when compared to horticulture. These soil management practices possible throughout combinable crop rotation are not feasible in vegetable or salad rotations given the need to extract root crops or individually harvest crop plants throughout the year. In the literature review, much of the work cited investigated the effect of a single CC species, as opposed to mixed species CCs. In the U.K., in order to fulfil the requirements of the Basic Payment Scheme, mixed species CCs must be grown. Finally, CC management, especially regarding CC termination (method of termination and time before establishment of the cash crop) can have a large effect on soil quality indicators and crop yield.

Given the lack of research into the effect of CCs on soil quality indicators in the U.K. the following knowledge gaps have been identified that are relevant to U.K. horticultural production: i) research relevant to agro-climatic regions (even within the U.K.), ii) organic soils used for crop production, iii) horticultural rotations as opposed to cereal/ combinable crop rotations iv) CC mixtures as opposed to a singles species CC and v) CC termination management that is dependent on the farm strategy (till or no till and organic or conventional).

Considering the aforementioned knowledge gaps, this research will investigate the effect of mixed species CCs within a horticultural rotation on the organic soils present in East of England.

1.7 Aim, Hypotheses and Objectives

1.7.1 Main Aim

The primary aims of this research were to:

1) investigate the effect of CCs on soil quality indicators in a horticultural rotation and
2) understand the use and management of CCs in U.K. agriculture.

1.7.2 Field Trial Hypotheses

To investigate the effect of CCs on soil quality indicators the following hypotheses were tested using field trials. The trials were established with different CC species relevant to their place within the cereal and horticultural rotation

Compared to a control (fallow) the implementation of a single CC period (8 months) between wheat and maize will:

1. improve soil structure and reduce soil compaction due to biopore creation from root growth and earthworm activity
2. decrease soil moisture ahead of maize establishment due to increased evapotranspiration during the period of CC growth
3. improve nutrient cycling; specifically by reducing soil available nitrogen (N) over autumn by CC uptake followed by an increase in soil available N after the decomposition of the CC due to frost senescence
4. increase earthworm population due to provision of habitat and food sources from the CC
5. increase microbial and fungal biomass, as well as microbial diversity community as a response to the presence and variety of CC species
6. increase soil organic carbon through the addition of CC residue
7. improve the yield of maize immediately after CC implementation and yields of lettuce following the maize

The implementation of a second CC period (initially established as a companion with maize) before lettuce establishment will:

8. augment the effects measured for hypotheses: 1, 4, 5 and 6.
9. decrease soil moisture ahead of the lettuce crop due to increased evapotranspiration from the growth of the overwinter companion crop
10. improve lettuce yield

The overall hypothesis is that CCs improved soil function and therefore lead to increased crop yields.

1.7.3 Objectives of the Cover Crop Survey

The objective of the CC survey was to further understand the use and management of CCs in U.K. agriculture. Specifically the survey sought to gain information from farmers on::

1) The area of CCs grown
2) The influence of tillage type on the use of CCs
3) The CC species used
4) Benefits noted from the use of CCs
5) Challenges associated with CCs
6) CC management – establishment and termination
7) Their opinions on the regulations of CCs in the Basic Payment Scheme 2016

1.8 Thesis Structure

The thesis structure is presented in paper format. Chapters 3-6 are standalone journal articles based on the results obtained from the survey and field trial work (Table 1.1). Chapters presenting the data from the PhD research are preceded by a short chapter (chapter 2) on trial design and followed by a final discussion chapter (chapter 7).

Table 1.1: Overview of the journal article chapters within the thesis.

Chapter number	Chapter title	Journal	Hypotheses
3	A UK survey of the use and management of cover crops (published)	Annals of Applied Biology	Objectives 1.7.3
4	Cover crops for timely nitrogen mineralisation and soil moisture management (submitted)	Agriculture, Ecosystems and Environment	2, 3 and 7
5	Limited effect of cover crops on soil structure in the short term (in progress)	Soil Use and Management	1, 6, 7 and 8
6	The effect of short term cover crops on earthworm, microbial and fungal communities (in progress)	Soil Biology and Biochemistry	4, 5, and 8

Table 1.2 shows the other presentations given during the PhD which utilised results obtained from the field trials and survey.

Table 1.2: Notable conference presentations

Conference	Presentation title	Presentation format
Sustainable Intensification Association of Applied Biologists (AAB) 2017	Do cover crops give short term benefits for soil health? (Storr et al., 2017a)	Poster & conference proceedings
	The use of cover crops in the UK: A survey (Storr et al., 2017b)	Poster & conference proceedings
Agronomic Conference International Fertiliser Society 2017	The effect of cover crops on the availability of nitrogen and phosphorus to following maize crop	Poster
World Congress of Soil Science Brazil 2018	Sustainable management of soil through the use of cover crops to aid maize production	Presentation
Soil Improvement: Impact of Management Practices on Soil Function AAB 2018	Soil water and available nitrogen during cover crop growth (Storr et al., 2018)	Presentation & conference proceedings

2 TRIAL DESIGN

The field trials took place over two growing seasons (2016 – 2018) and on two individual field sites, Prickwillow and Littleport - both located near Ely, Cambridgeshire. The trial was based around a wheat – maize – lettuce rotation. CCs established after wheat harvest are referred to as phase 1 and is the first CC period. Given the late harvest of maize and potential difficulties of establishing a CC after maize harvest due to poor soil conditions and a shorter growing period, it was decided that the second CC period (phase 2) would be established as a companion crop at the same time as maize establishment. A companion crop is a secondary plant species established alongside the primary crop (maize). The companion crop became an over winter CC after maize harvest until lettuce was planted in June the following year. A schematic of the trial is shown below (Figure 2.1). Phase 1 was trialled at both Prickwillow and Littleport. Phase 2 was established following phase 1 at Prickwillow only. Appendix A gives a brief timeline of the operations and sampling that was undertaken on the trial sites.

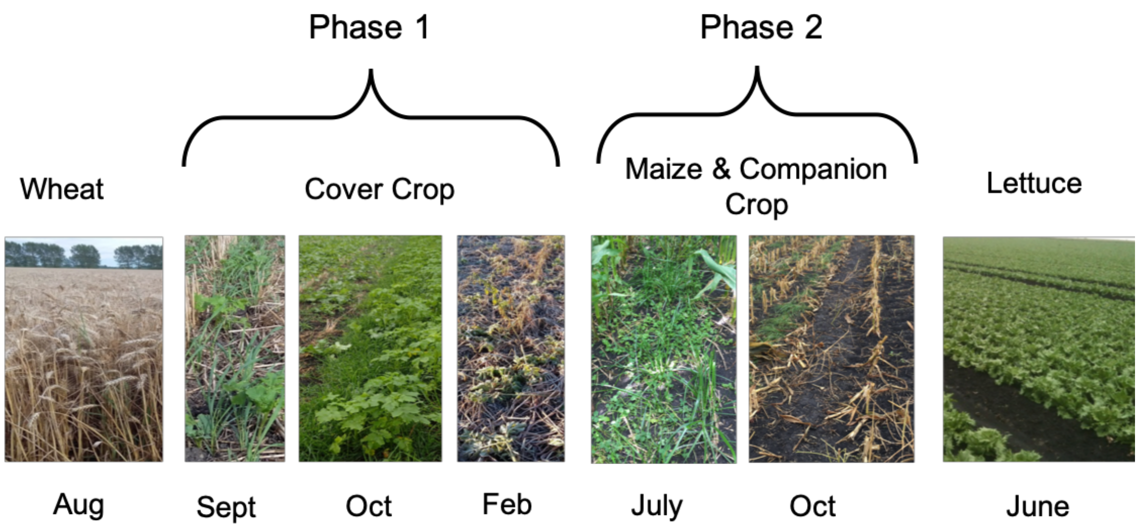

Figure 2.1: An overview of the trial rotation and placement of phase 1 and phase 2 cover and companion crops between 'wheat – maize' and 'maize – lettuce', respectively.

2.1 Cover Crop Selection

There are many different plant species that could be utilised as a CC. It was decided that CC mixtures would mitigate the risk associated with establishment and growth of a new single species CC in the rotation (Measures, 2015). The decision was also made to establish two different CC mixtures differing in their sensitivity to frost as this may have management benefits. The two CC mixtures i) winter hardy (WH) and ii) frost sensitive (FS) are outlined in (Table 2.1). To ensure the CC mixtures were commercially acceptable, the species composition and varietal selection was assisted by Simon Hobbs – national seed manager, Agrii.

Table 2.1: Cover crop species contained within the two mixtures.

Frost sensitive mixture (25 kg Ha^{-1}) £42 ha^{-1}	Winter hardy mixture (30kg Ha^{-1}) £36 ha^{-1}
60% Cadence black oats *Avena stigosa cv.* Cadence	60% Protector forage rye *Secale cereal cv.* Protector
35% Final oil radish *Raphanus sativus cv.* Final	30% Evergreen oil radish *Raphanus sativus cv.* Evergreen
5% Braco White mustard *Sinapis alba cv.* Braco	10% Berseem clover *Trifolium alexandrium cv.*

Both mixtures were based on a cereal and brassica species (>90%) and differentiated by either the inclusion of an additional brassica (FS) or a legume (WH). A mixture of CC species can provide multiple desirable characterises (N service, biodrilling and mulching effects) (Chen & Weil, 2010; Couëdel et al., 2018). Cereals were selected for their fibrous root system to provide a diversity of root structure when established alongside the tap root of the oilseed radish. It was anticipated that the oilseed radish would help relieve compaction and create large biopores, whilst the fibrous roots of cereal component would lead to better aggregation (Chen & Weil, 2011; Liu et al., 2005). The inclusion of mustard would provide rapid ground cover and once terminated would provide some surface residue (Bodner et al., 2010). The inclusion of berseem clover adds a legume to the WH mixture and although sensitive to cold temperatures, could increase the diversity of the soil biological community.

2.2 Companion Crop Selection

Companion crop selection was based on observations of a pilot trial (Appendix B) to assess the establishment of different plant species as potential companion crops with maize. This pilot study was conducted in May 2016 on a field of similar soil type to the main field trial and consisted of 4 companion crop treatments broadcast by hand at maize leaf stage 5. Additionally, a visit to the trials based at Reaseheath College conducted in partnership with Agrovista and Pöttinger UK helped inform seed selection as well as discussion with Simon Hobbs, Agrii (Reaseheath College, 2016).

The companion crop selected was 6kg ha^{-1} tall fescue (*Festuca* arundinace cv Starlet) and 1 kg ha^{-1} white clover (*Trifolium repends)*. Tall fescue is slow growing grass species that would help to mitigate competition with the maize crop. White clover adds diversity to the companion crop mixture and may be expected to fix N prior to maize canopy closure over the summer period.

2.3 Drill Selection

A 6m Horsch sprinter ST drill with tine coulters was used to establish the CC of phase 1. This drill is not used to establish maize on the farm and is completed by a contractor using a specialist wide row maize drill. Both the Horsch Sprinter ST and specialist maize drill were not suitable for establishment of the companion crop with maize for phase 2.

Establishment of companion crops in the U.K. is not a big market and this is reflected in the drill availability capable of establishing a companion crop with maize. A companion crop with maize may be established at the same time as maize establishment or after maize establishment.

In this trial, the use of shallow or ideally zero till was also a requirement of maize and companion crop establishment. Limiting soil disturbance at this stage of the trial (post phase 1 CCs) would allow any effects of the CC to accumulate over time with continued plant presence and therefore differences in soil quality indicators may be measurable following phase 2. However, at the time of companion crop establishment only two methods were available in the U.K. to establish a companion crop at field scale. The first required an additional operation to maize establishment as the companion crop would be established at maize leaf stage 4-6. This was deemed unsuitable for two reasons i) a separate operation would add cost and time and ii) damage caused to the maize crop during headland turning would reduce maize yield. The second option utilised a drill that established maize and the companion crop at the same time but in separate and defined rows, however it had only been implemented in trials in conjunction with a powerharrow on clay soils at the Reaseheath trials. This was the Aerosem 3002 ADD drill available from Pöttinger UK.

Following discussion with Pöttinger UK, we changed the drill set up and removed the power harrow from the Aerosem 3002 ADD drill and replaced it with Fox D discs (cultivation depth 0.08m). This compromise would allow the simultaneous drilling of the maize and companion crop whilst minimising soil disturbance. The drill had a spilt hopper that allowed maize to be established at

0.75m row widths and companion crop seed at 0.125m row spacing between the maize coulters. The coulters can be independently turned on or off. The coulters immediately next to the maize coulters were turned off to reduce the chance of competition between the maize and companion crop (CpC). The resulting pattern of row establishment was maize-empty-CpC-CpC-CpC-empty-maize.

2.4 Field Trial Layout

Both field trials were located near Ely, Cambridgeshire. The first trial at Prickwillow was located on the field Kings 8, which was deemed to be most uniform in soil texture and a suitable size (6 ha). The second field trial was located near Littleport, Ely and was established within the field, Jacks and Porters. Prickwillow hosted both phase 1 and phase 2 of the field trials, and Littleport hosted a repeat of phase 1. Below is an overview of the field trial layout with more detailed sampling protocol contained with the following chapters.

2.4.1 Prickwillow

CCs (frost sensitive (FS) and winter hardy (WH)) were established on the 26th August 2016 in 24m x 80m plots following wheat harvest (phase 1). The companion crop (CpC) of phase 2 was subsequently established perpendicular to the plots of phase 1 in 12 m wide rows on 11th May 2017. This creates a mosaic of plots (24m x 12m) across the field site (Figure 2.2), of which 5 of the 9 replicates per treatment were randomly sampled at the end of phase 1 and 2.

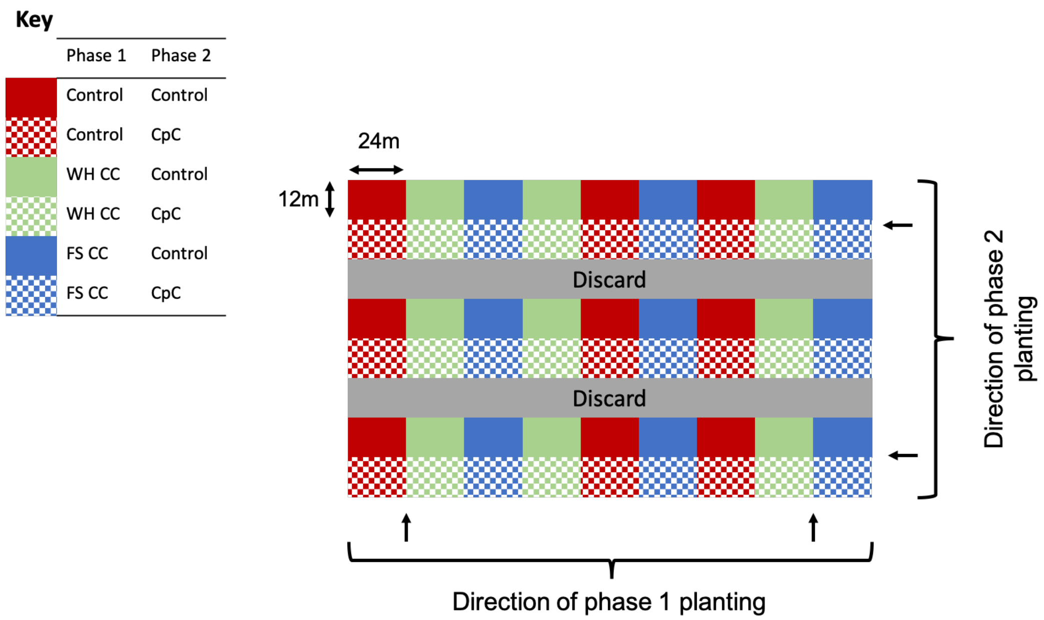

Figure 2.2: Schematic of field trial layout at Prickwillow for phase 1 and 2.

2.4.2 Replicates

The decision was made to pool the results from the two CC treatments as both resulted in a cereal and brassica CC mixture as the berseem clover did not establish well in the WH CC treatment (Appendix C). Thus, the CC treatments only differed by growing characteristic and sensitivity to temperature. This resulted in unequal sample sizes following phase 1 (Table 2.2) and phase 2 (Table 2.3).

Table 2.2: Phase 1 sample size.

Treatment	Replicates
Control	10
Cover crop	20

Table 2.3: Phase 2 sample size.

Treatment	Phase 1	Phase 2	Replicates
Control	Control	Control	5
Cover crop	Cover crop	Control	10
Companion crop	Control	Companion crop	5
Cover & companion crop	Cover crop	Companion crop	10

2.4.3 Littleport

The CCs were established on the 24th August 2017. Trial plots were 24m wide and extended 100m into the field (Figure 2.3). There were three replicates of the control and FS CC treatment. Only the FS CC treatment was trialled at Littleport as it was more practical to manage at field scale than the WH CC.

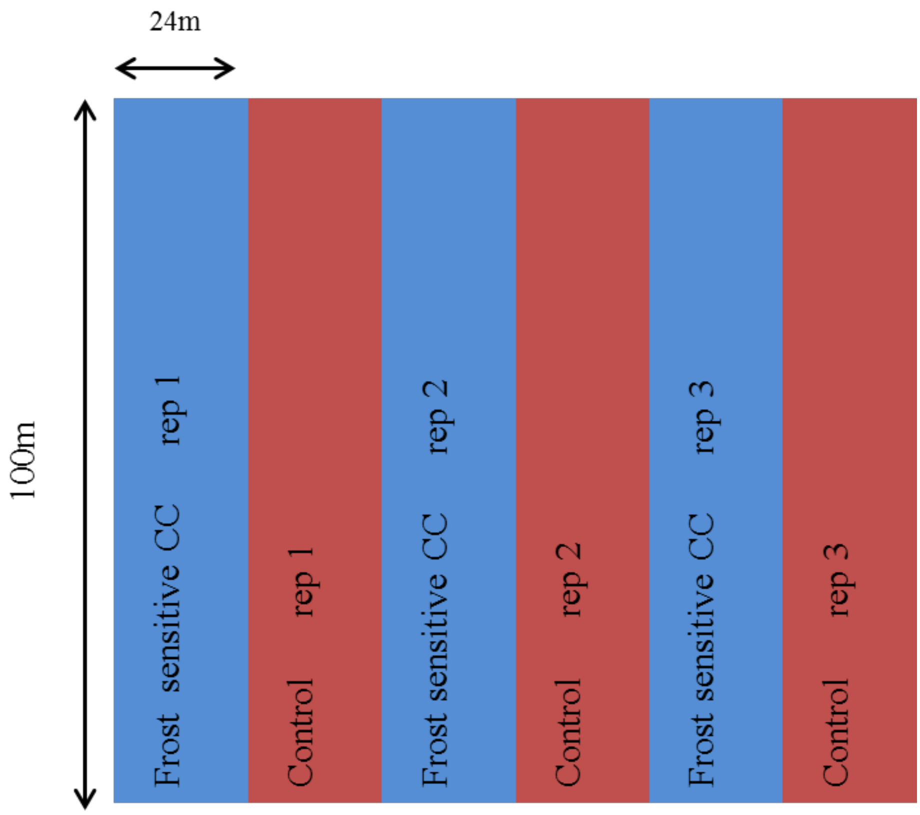

Figure 2.3: Schematic of the field trial layout at Littleport.

NB. Plots are not to scale but are for illustrative purposes only. Rep indicates replicate.

2.4.4 Field Trial Design Evaluation

Field trials were designed with a minimum of three replicates and to some extent randomisation. However, it is acknowledged that this fell short of best practice - 4 replicates and complete randomisation.

The field trial had to remain commercially viable and was maintained using the machinery of the host farm. Working widths of the machinery dictated plot and replicate widths and thus the number of replicates that could fit within the given field. Secondly, it was not possible to achieve complete randomisation in the field trial at Prickwillow as it would be extremely time consuming for the operator to implement using a 6m drill.

3 A U.K. SURVEY OF THE USE AND MANAGEMENT OF COVER CROPS

3.1 Abstract

There is a growing trend in the use of cover crops (CCs) in the United Kingdom, and whilst research shows that there are many soil and environmental benefits, little is known about the farmer's perspective of cover cropping. A survey was designed and distributed to ask farmers about their use and management of cover crops. The online survey received 117 usable responses between January and March 2017, following distribution through social media in the UK. The survey highlighted that 66% of respondents used CCs following harvest in 2016. Respondents observed benefits to soil structure, soil erosion control and water infiltration in addition to reductions in the use chemical fertilisers, herbicide and fuel use. Of those not using CCs, 90% would consider their use in the future if additional information on their use and benefits were known in a U.K. context. Changes to the 2016 Basic Payment Scheme guidelines for CCs would have been welcomed by 71% of respondents using cover crops.

3.2 Introduction

Cover cropping is gaining momentum in the U.K. Extensive research, largely conducted outside of the UK has shown that CCs can benefit: soil structure (Munkholm et al., 2013; Tonitto et al., 2006), soil biology (Reeleder et al., 2006; Roarty et al., 2017) soil erosion control (Magdoff & van Es, 2000) and nutrient management (Cooper et al., 2017; Wendling et al., 2016). Cover cropping therefore helps to improve soil quality and the wider environment such as water quality and biodiversity (Prechsl et al., 2017)

There is an increasing awareness of sustainably managing soils, with farmers and the UK government recognising the importance of soil to deliver ecosystem services and provide food. The strategy for 'Safeguarding our Soils in England' (DEFRA, 2009a) proposed the sustainable management of soils by 2030, and elimination of soil degradation. DEFRA continues to support the management of UK soils to balance sustainable, reliable and profitable food production whilst protecting the environment (AHDB, 2018; DEFRA, 2018a). Soil faces a number of threats with soil erosion, soil compaction, loss of organic matter and climate change as the principal concerns for soils in England (DEFRA, 2009b). CCs may be used to address these threats (Maetens et al., 2012; Posthumus et al., 2015; Williams & Weil, 2004).

The Common Agricultural Policy (CAP) was reformed in 2013 (Zinngrebe et al., 2017) and from 2015, 'Greening Measures' incentivised the use of cover and/or catch crops under Ecological Focus Areas (EFA) in the Basic Payment Scheme (BPS). Guidelines for the use of cover and catch crop species under BPS claims are regulated by the Rural Payments Agency (Rural Payments Agency, 2016) in England. These rules stipulated that cover and catch crops must be a visible mixture of at least two different crops from a prescribed list of 8 species, where one species in the mixture must be a cereal (rye, barley, oats) and the other a non-cereal (vetch, phacelia, mustard, lucerne and oilseed radish) species. Additionally, cover and catch crops must remain over a specified period. In 2015/16, 55,900 ha were planted with cover or catch crops as an EFA feature, representing a 45% increase from the previous season (DEFRA, 2017).

Scientific research supports the use of CCs to reduce nitrate leaching (Cooper et al., 2017; Macdonald et al., 2005), improve soil structure (Chen & Weil, 2010; Stobart et al., 2015) and for weed management (Crotty & Stoate, 2017; Schulz et al., 2013). Earthworms are important soil structural engineers that create biopores for water infiltration and plant root growth, as well as serving an important role in nutrient cycling and availability (Stroud et al., 2016; Yvan et al., 2012). However, the use of CCs does not always support increased populations of earthworms (Roarty et al., 2017; Stroud et al., 2017). The benefits associated with CCs may be weather dependent. The use of soil moisture by a CC may be beneficial if rainfall has been plentiful (i.e. removing excess soil water) but can be detrimental if rainfall has been low (removing limited soil water). Nitrogen fixation by leguminous CCs is also temperature dependent (White et al., 2016).

In the United States, farmers' experience of cover cropping has been identified through an annual CC survey that started in 2012 and now attracts over 2000 responses. The surveys have recorded the trends, management and general metrics of CC use in the USA and the effect of CCs on the yield of the follow-on crop (CTIC, 2017). However in the U.K., little is known about the farmers' experience of CCs and if the benefits reported in the scientific literature from controlled laboratory and/or field experiments are materialising on farm. On farm, CCs need to be practical to implement – but little is known about the management considerations of using CCs given the lack of relevant research literature for applications in a UK context. EFA 'Greening Measures' incentivised the use of cover/ catch crops and feedback on the efficacy of CC implementation would help improve the rules in future agricultural legislation. Changes to UK agricultural legislation are imminent given the Government's 25 year Environment Plan (DEFRA, 2018a) and recent consultation paper (DEFRA, 2018b).

This paper aims to present information from farmers about the use and management of CCs in the U.K. using a survey distributed to the U.K. arable farming community in winter 2017. The survey collected information on the benefits and challenges of using CCs and the farmer's opinion on CC regulations under the ‘Greening Measures’ from BPS 2016 (Rural Payments Agency, 2016). The study aimed to provide insights into the rapidly growing trend in the use of CCs in the UK.

3.3 Materials and Methods

3.3.1 Survey Implementation and Distribution

A U.K. survey (Appendix D) aimed at arable and horticultural growers was distributed from January to March 2017. The survey was developed using Qualtrics software (Qualtrics, 2005), an online survey platform. An online survey method was chosen as the farming community has a large and active online presence and is inexpensive and easy to administer and manage. Survey links were distributed via twitter, The Farming Forum, emails (to known contacts), and to agronomy companies. No funds were used to advertise the survey. The survey link was tweeted several times from the author's account and accumulated a total of 19,188 impressions, 614 engagements, 80 retweets and 161 tweeters clicked the link; additionally, The Farming Forum post received 581 views. Feedback was obtained from industry professionals at several stages of survey development to ensure the questions were unambiguous and the survey flowed logically for participants. The survey was entitled 'Sustainable Soil Management' to avoid biasing results in favour of only CC respondents.

3.3.2 Survey Content

Prior to answering any questions participants were informed about the intent of the survey and how the data would be used and stored. Participants could decline to take part having read this information.

The survey was split into 6 sections: farm demographic information (Section 1), crop establishment/ tillage (Section 2), non-use of CCs (Section 3), overview of CC use (Section 4), CC management (Section 5) and soil health (Section 6). The survey contained two pathways; farmers that used CCs answered Sections 1, 2, 4, 5, and 6, and farmers not using CCs answered Sections 1, 2, 3 and 6.

All survey participants were invited to give their name and contact details if they wished to be entered into a prize draw for Groundswell Agriculture event tickets.

Data was anonymised and stored according to data protection guidelines at Cranfield University.

From 226 respondents who started the survey there were 117 usable responses; this represents 0.19% of agricultural holdings that are classed as cereals, general cropping, horticulture and mixed farms (Armstrong, 2016; DAERA-NI, 2017; DEFRA, 2018c; Scottish Government, 2017). Responses were deemed usable if respondents had completed at least section 3 and 4 if they were a non-CC and CC user, respectively. Full responses (all sections completed) accounted for 69/78 and 35/39 for CC and non-CC users, respectively. Responses were excluded if they did not fulfil the completion criteria outlined above (n =109). In addition three full responses were discarded because two were from non-arable farms and one response was received from outside the UK. For many of the UK regions, 8 or more responses were received except: Wales (0), Northern Ireland (n = 1), Scotland (n = 2) and North West England (n = 2). Collectively 59,890 ha were farmed by the 117 respondents of which 36,584 ha were planted with combinable crops.

3.3.3 Data Analysis

CC species specific data was broadened to genus level groups e.g. fodder radish and oilseed radish were both classified as radish. Soil texture data was also aggregated to heavy, medium and light soils following DEFRA Cross Compliance Guidance (DEFRA, 2006). Heatmaps of CC species used on each soil texture class (heavy, medium, light) were produced in the free open source software R. Data from Qualtrics and were imported into Excel where summary statistics (percentages) from the answers provided to questions were calculated.

3.4 Results

3.4.1 Cover Crop Use

Following harvest 2016, CCs were used by 66% (n = 117) of survey respondents. On average 21% of the farm area per farm was planted to CCs. The 39 respondents not using CCs (following harvest 2016) cited the following top 3 reasons for lack of adoption i) they do not fit the current rotation ii) expense and iii) hard to measure their benefit.

CCs were used across all tillage types, though CCs were more prevalent on reduced tillage farm systems (Table 3.1). Those practising zero till or strip till were more likely to use CCs compared to those who power harrow, direct drill and plough.

Table 3.1: Cover crop use related to dominant tillage type present on farm.

Dominant Tillage Type	Proportion of farms using cover crops per tillage type, %
Mixed[1]	100 (n = 2)
Zero Till	95 (n = 20)
Strip Till	86 (n = 7)
Deep Tillage	80 (n =10)
Shallow Tillage	70 (n = 10)
Plough	54 (n = 46)
Direct Drill	54 (n = 13)
Subsoil	50 (n = 4)
Power Harrow	40 (n = 5)

[1] Mixed tillage describes farms where tillage used was dependent on crop grown. E.g. zero till for spring barley whilst winter wheat was power harrowed and sub-soiled.

Over half (56%, n = 78) the CC users had 3 years or less experience of using CCs. Figure 3.1 highlights that farmers who have used CCs for longer are more likely to observe a benefit to soil structure.

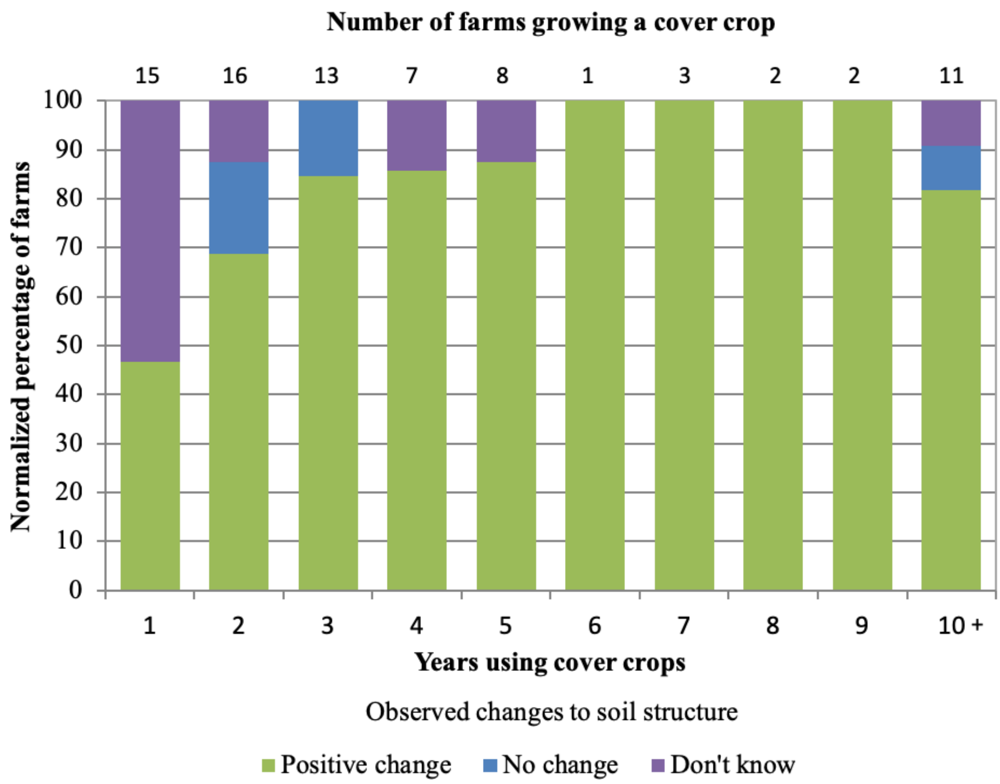

Figure 3.1: Proportion of respondents (n=78) reporting a benefit to soil structure broken down by number of years respondents had been growing a cover crop.

Figure 3.2 shows that farms on heavier soils had a high use of radish and oats in their CC. Those on light soils tended to include clover and phacelia. On average, respondents paid £30.30 per ha for CC mixtures and £22.80 per ha for a single CC species. A single species CC only accounted for 18% of the respondents, whilst 2-3 and 4+ CC species mixtures accounted for 51% and 31% of respondents, respectively (n = 78). Of those who used a mixed species CC only 27% used a pre-packaged commercially available mixture, 30% had a custom CC mixture blended and the remaining 44% of respondents prepared their own mixture (n= 64). In the first two years of growing CCs 54% (n =26) of respondents purchased a pre-packaged CC, this decreased to 4% (n = 25) and 18% (n = 13) after 3-6 years and 7-10years+ of CC experience, respectively.

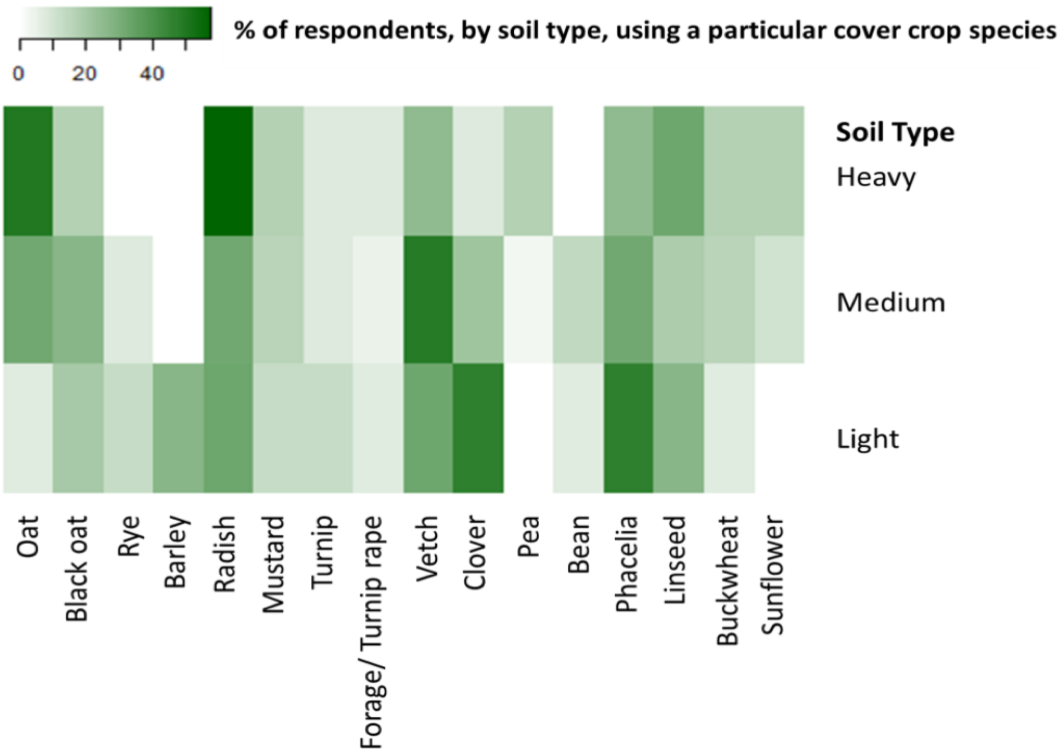

Figure 3.2: A heatmap showing the percentage of respondents who used a particular cover crop species, per soil type.

3.4.2 Perceived Cover Crop Effects on Soil Quality Indicators

Over 70% (n = 78) of respondents who used a CC reported a benefit to soil structure, earthworm numbers and soil erosion control (Figure 3.3) although soil type was found to be an influencing factor in the latter. No respondents reported a negative effect of CCs on soil structure, earthworm numbers or soil erosion control. 82% (n = 17) of respondents farming light soils reported a benefit to soil erosion control using CCs compared to 64% (n = 14) on heavy soils. Benefits to organic matter and drainage/infiltration were observed by 52% and 63% (n = 78) of respondents, respectively. There was greatest uncertainty of the effects of CCs on organic matter and nutrient availability, as these returned the greatest number of 'don't know' responses. Also, following CCs one respondent noted that nutrient availability and the number of working days were negatively affected.

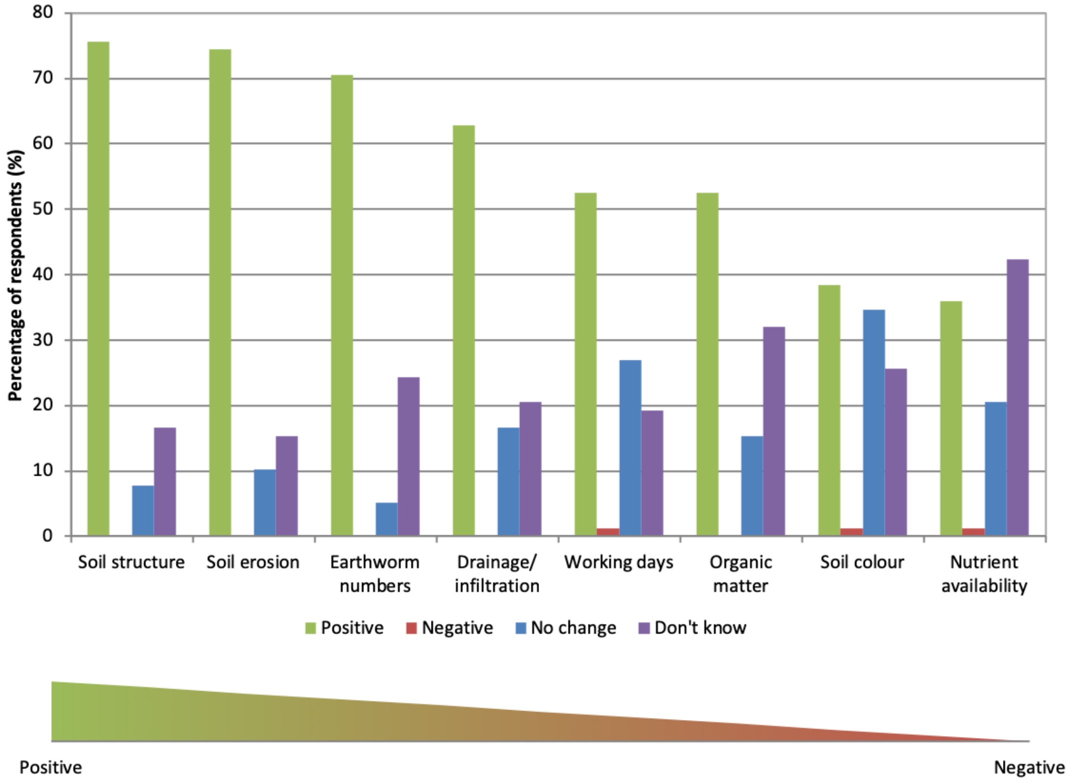

Figure 3.3: Perceived effect of cover crops on soil quality indicators.

3.4.3 Cover Crop Effect on Yield

Yield benefits following a CC were reported by 22% (n=77) respondents in a number of crops (wheat, sugar beet, spring barley and linseed). Nine respondents were able to quantify the benefit. Three respondents reported 0.2, 0.4 and 0.5 t ha^{-1} increase in winter wheat yield, with a 0.25 and 0.5 t/ha increase reported in spring wheat and spring barley, respectively. Two respondents reported a 3 and 5 t/ha increase in sugar beet yield. A 50% increase in linseed yield was reported by one respondent. However, 2 respondents reported yield decreases in spring barley and spring bean crops of 1 t/ha for each crop. No change to yield was reported by 23 respondents and 35 respondents didn't know.

3.4.4 Cover Crop Effects on Land Management and the Environment

Figure 3.4 highlights that herbicide and chemical fertilizer use has been reduced by 27 and 26% (n = 78) of respondents who used CCs, respectively. However, 29% of respondents reported an increase in the use of slug pellets with 35% of respondents noting an increase in slug populations, though no change in slug populations was observed by 41% of respondents (n=78).

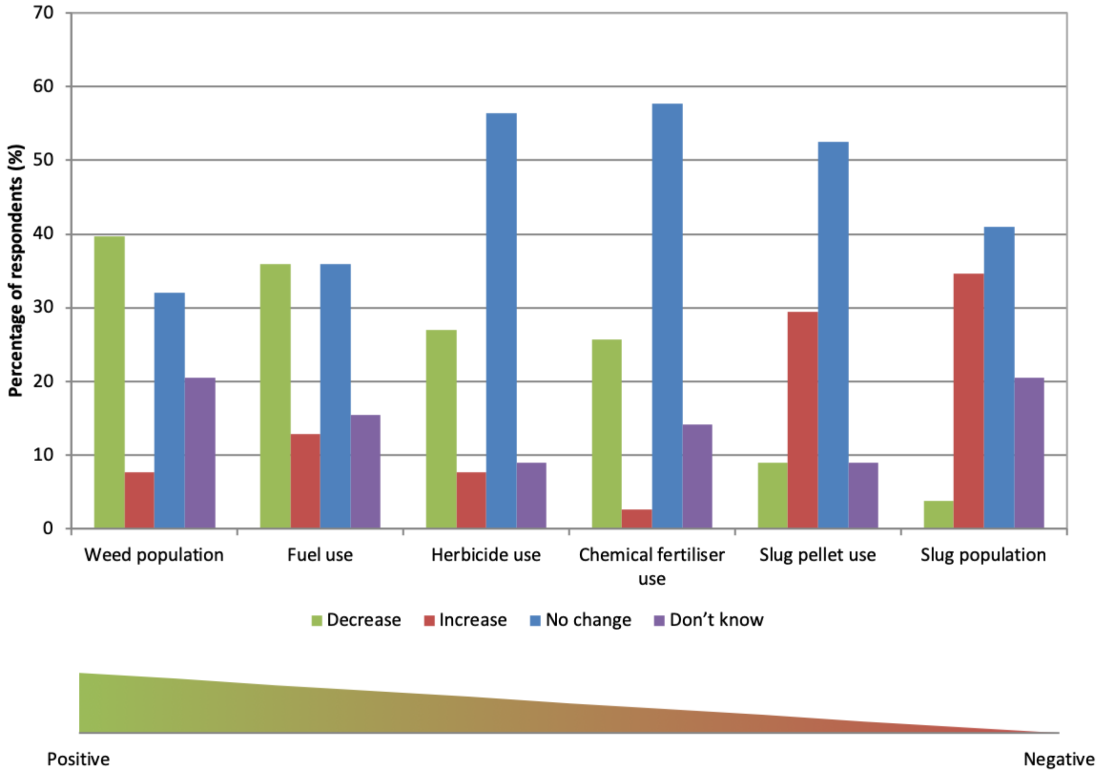

Figure 3.4: Perceived effect of cover crop practices on land and crop management.

3.4.5 Cover Crop Management Challenges

Time and labour requirement (n=78) for the cultivation of CCs was reported as a challenge (Figure 3.5) with 17 and 40% of respondents reporting that it was 'always' or 'sometimes' an issue, respectively. However, 37% of respondents reported that the time and labour requirements associated with CCs had never been an issue. In addition, 55% of CC users reported that CC establishment (n = 78) was 'sometimes' an issue and 10% of respondents indicated that it was always an issue. CC establishment had ‘never’ been an issue for 19% of respondents and 13% reported that CC establishment was ‘no longer’ an issue. Disease concerns (n = 78) following a CC had never been a problem for 70% of the respondents using a CC, only 12% indicated that disease was sometimes a challenge.

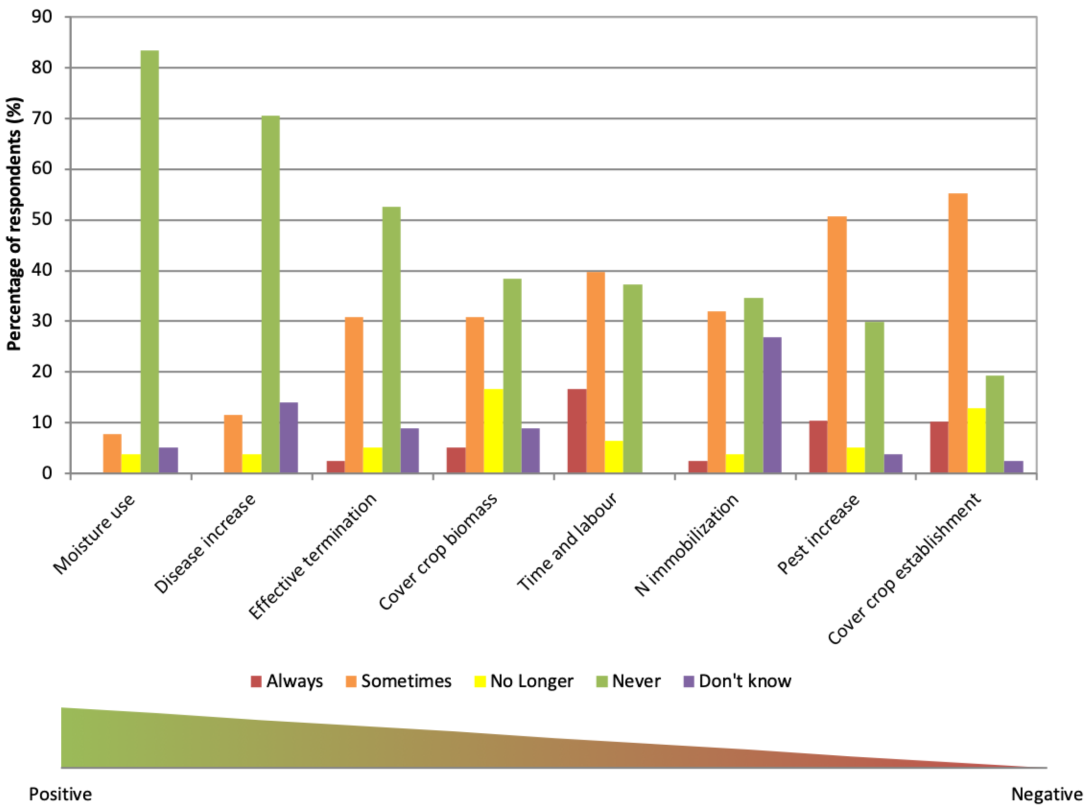

Figure 3.5: Challenges experienced by those using cover crops.

Biomass refers to problems that may result from the plant material being too large or having an architecture that interferes with establishing the next cash crop. Moisture use refers to the concern that CCs may use too much water, creating problems for the establishment of the following crop.

3.4.6 Cover Crop Termination

Herbicide was the most frequent method used to terminate CCs (81%, n = 69), with the majority of the remaining respondents (17%) using some form of cultivation or biomass removal (mowing or grazing). One respondent growing a

CC mixture of oilseed, fodder and rooting radish relied on natural senescence in order to terminate the CCs.

3.4.7 Supporting Cover Crop Use

Of the respondents not using CCs following harvest 2016, 92% (n = 39) would consider their use in the future. The following top 3 reasons would influence their decision to consider using CCs in the future i) more detailed information on the economics of cover crops ii) more detailed information on the effect of cover crops and how to measure this on the farm and iii) access to funds/ grants to help with seed purchase and establishment costs.

3.4.8 Policy Supporting Cover Crop Use

Of the respondents who used CCs, 71 % (n = 75) indicated that the EFA guidelines (The Basic Payment Scheme rules for 2016 (Rural Payments Agency, 2016)) for cover (and catch) crops were not suitable. Many respondents (n = 37) gave recommendations for the improvement of EFA guidelines on the use of CCs. A selection of the comments are reported below:

‘A greater diversity of crops to be included on the list of crops. I have cover crops that are too diverse to qualify as EFA’

‘To include other mixes that are more pertinent to our cropping regime, soils and area’

‘More species. Being allowed to graze them’

‘They are too prescriptive, there is no room for any experiments’

‘Include single species cover crops’

A change in the EFA guidelines for CC species would encourage 20% (n = 39) of the respondents currently not using CCs to do so in the future.

3.5 Discussion

3.5.1 Cover Crop Use in the U.K.

A current trend in U.K. agriculture is the increased use of CCs. The survey results support this view as 56% of respondents had ≤ 3 years experience of using CCs and 75% of respondents have used CCs for ≤ 5 years (Figure 3.1). U.K. agriculture is relatively new to the use of CCs compared to the USA and France. CC use in the United States became more prominent following the formation of the Sustainable Agriculture and Research Education (SARE) program in the 1990’s (Groff, 2015). A survey conducted in the United States between April and May 2017 reported that 88% of respondents (total respondents =2102) used CCs, of which only 37% had ≤ 3 years’ experience of using CCs (CTIC, 2017). Since 2001, French farmers have been obliged to maintain winter soil cover, and autumn CCs have been mandatory for all nitrate vulnerable zones since 2008 (Justes et al., 2012). There is greater use of CCs in reduced tillage systems (zero till and strip till) in both the results presented in this article and in the USA survey (CTIC, 2017). Farms practicing zero till are likely to be reliant on CC root growth to perform ‘bio-tillage’ of the soil. The biopores created are preserved by the lack of tillage and aid the following crop’s root development (Stirzaker & White, 1995; Williams & Weil, 2004).

Of those without previous experience of CCs, the majority of respondents used pre-packaged and commercially available CC species. However, after 2 years of CC experience there is a sharp decline in the use of pre-packaged commercial mixes; instead respondents prepare their own CC mix or customise mixes - perhaps as a result of their increased experience and knowledge of what works well for their own circumstances. In the U.K. survey, the use of CC mixtures far out-weighed the use of a single species CC. A similar trend was observed in the USA where 65% of farmers planted CC mixtures (CTIC, 2017). CC species mixtures are recommended for multiple ecosystem services (Couëdel et al., 2018) although a single CC species may be more economical and sufficient for the desired management goals (Finney et al., 2016).

On heavier soils, 58% of respondents selected a species of radish in the CC mix. Research has shown, that radish, with its strong tap root is able to alleviate mild compaction (Chen & Weil, 2010), which is a top priority for farmers on heavy soils. Those farming medium textured soils ranked the improvement of soil biology as a top reason for growing CCs. The legume, vetch, was a common CC species choice for respondents farming medium soils, which may help to achieve their aim of improving soil biology; legumes (e.g. peas) have been known to increase earthworm biomass and abundance compared to brassica and some graminacea species CCs (Roarty et al., 2017). Additionally, legume CCs permit greater arbuscular mycorrhizae fungi colonisation of the cash crop (maize, oat, other legume) roots than graminoid or non-legume dicot CC groups (Bowles et al., 2017). The survey in the United States reported that CC species selection has been consistent for several years. Cereal rye, radish, crimson clover and buckwheat were the most popular choices for the cereal grain, brassica, legume and summer annual CC groups, respectively (CTIC, 2017). The wide spread use of cereal rye and ryegrass in the USA is not observed in the UK. The cereal component of CCs in the UK is dominated by the use of oat varieties; the reason for this is not clear but could be related to suggestions from seed companies that advise farmers that are new to using CCs.

3.5.2 Cover Crop Effects on Soil Indicators

Changes to soil properties due to CCs take time. Jokela *et al.,*(2009) reported that after 4 years of CC growth there were no pronounced changes in soil quality indicators (total organic carbon, aggregate stability, pH, phosphorus and bulk density). The survey showed that in the U.K. after one year of using CCs 47% of respondents observed a benefit to soil structure but this increased to 80% after ≤3 years of CC use. The survey highlighted that 92% of respondents (n=103) answering the soil health section, took a spade ‘to dig and have a look’ at soil structure with 51% of these respondents following a prescribed method such as the visual evaluation of soil structure (Guimarães et al., 2011). This is similar to farmers in the USA where 54% observed a benefit to soil health in <2 years and a further 21% observed a benefit to soil health in 2-3 years (CTIC, 2017). Figure 3.3 shows that a substantial percentage of respondents using CCs noticed an improvement to soil erosion control, drainage & infiltration and earthworm numbers. Research supports the use of CCs for soil erosion control (Posthumus et al., 2015) and water infiltration (Folorunso et al., 1992) although increased earthworm numbers after CCs is not always reported (Roarty et al., 2017; Stroud et al., 2017).

3.5.3 Crop Yield

There was a mixed response from respondents regarding knowledge of crop yield following the use of CCs. The majority of respondents ‘didn’t know’ if yield had improved following CCs. Only two respondents reported yield reductions in spring crops following CCs; both respondents farmed on heavy soils using a reduced tillage system of direct drill and zero till. The lack of consensus on the effect of CCs on the follow-on crop yield has also been widely reported; reduced yield (Stobart & Morris, 2015), no change to yield (Basche et al., 2016; Gabriel & Quemada, 2011) and increases to yield (Bensen et al., 2009; Chen & Weil, 2011). The American National Cover Crop Survey (Conservation Technology Information Center 2017) reported a statistically significant increase in yield of 1.3% and 2.8% for maize and wheat crops, respectively. Even within studies, different CC species can be favourable or detrimental to crop yield (DuPont et al., 2009; Jahanzad et al., 2017; Kramberger et al., 2009). It is evident that CCs can affect yield positively, negatively or not at all and that this will be related to the CC species used, effectiveness of termination and climatic conditions.

3.5.4 Effects of Cover Crops on Land Management and the Environment

CC users observed changes that have potential positive impacts on the environment and ecosystem services such as reduced use of herbicide, chemical fertiliser and fuel. Whilst CCs are not the sole reason for these beneficial outcomes, they are part of broader changes to farm management practice such as reduced or zero tillage. The reduction in herbicide, chemical fertiliser and fuel use, partly through the use of CCs can help improve air and water quality. Although herbicide is also used for CC termination, the reported decrease in herbicide use relates to overall reduction across the farm, potentially as a result of reduced weed burden associated with CC use and reduced tillage (Osipitan et al., 2018). Leaching of nitrate and phosphate fertilisers are the main pollutants of watercourses (National Audit Office, 2010; Stoate et al., 2001), therefore, farm management practices that reduce their use will be beneficial to water quality. Carbon sequestration can be facilitated through the use of CCs and has been estimated to be sequestered at a rate of 0.32±0.08 Mg of C Ha^{-1} yr^{-1} (Poeplau & Don, 2015).

This UK survey does highlight one management issue of CCs that can have a negative impact on water quality – the increased use of slug pellets to control slug populations as a result of using CCs. Metaldehyde present in some slug pellets is often detected in surface water above the EU statutory drinking limit (Castle et al., 2017). However, it should be noted that 53% of respondents report no change in their use of slug pellets whilst using CCs. Slugs are a major crop pest and if not controlled can reduce wheat and oilseed rape yields by 5 and 4%, respectively, (Clarke et al., 2009) costing an estimated £43.5m per annum in the UK (Nicholls, 2014). A number of strategies can be utilised to manage slug populations and/or reduce the use of slug pellets when using CCs. Vernavá *et* al.,(2004) reported that slug populations were greater following vetch or red clover than ryegrass. This suggests that CC species is a factor in determining slug populations, thus CC species selection could be managed accordingly. Additionally, grass lined channels (swales) can be used to control the velocity of run-off (DEFRA, 2011a), the use of ferric phosphate rather than metaldehyde and payments for non-use of metaldehyde within high risk catchments may help to reduce the effect of slug pellets on the environment (Castle et al., 2017).

3.5.5 Challenges of Cover Crop Use

CC users indicated that time and labour requirement for CC operations is a challenge. Often CCs are established as soon as possible after harvest of the previous crop in order to give sufficient time for growth and biomass accumulation before CC termination. However, the establishment of CCs can compete with time needed for wheat harvest and oilseed rape establishment. Additionally, there will be CC termination operations performed in the following winter/ spring. Participants of focus groups in the United States also highlighted the time management challenges associated with CCs but viewed such challenges as management opportunities to adapt practice in a 'whole system' approach through trial and error (Roesch-McNally et al., 2017).

The high number of 'Don't know' responses concerning N-immobilization by CCs, highlights an area that requires further research in the UK to better inform farmers. Research would enable farmers to better manage the termination of their CCs so that N- immobilisation is better understood for U.K. soils, climate and cover crop species used. Other notable challenges that could be a focus for the research community, in collaboration with the farming community, is the pest increase that is reported as 'sometimes' an issue by 51% of the farmers using CCs (Figure 3.5) and this is further supported by the issue of slugs (Figure 3.4).

3.5.6 Considerations for Future Cover Crop Use

Herbicide (presumably glyphosate but the survey was not specific) was used by 81% of respondents to terminate the CC. In December 2017, the European Commission approved the use of Glyphosate for a further 5 years until 2022 (European Commission, 2018) after much debate due to it being a possible human carcinogen (Tarazona et al., 2017). Furthermore, glyphosate resistant weeds are reported in Australia and the United States (Heap & Duke, 2017). As it is possible that the chemical may be withdrawn from use in the near future, farmers and researchers should focus on the investigation of alternative and effective methods of CC destruction. Finding alternative means to terminate a CC will add resilience into the management of CCs and maintain their use and benefit to the wider environment.

The majority of respondents currently not using CCs would consider their use in the future provided there is information and support with i) more detailed information on the economics of cover crops ii) more detailed information on the effect of cover crops and how to measure this on farm and iii) access to funds/ grants to help with seed purchase or establishment costs. In the USA, similar factors influencing CC uptake were reported. Cost share (the contribution of funds per acre for growing CCs) or incentives were the top influencing factor for farmers to start using CCs, followed by free technical assistance, more information about CC species and local field demo plots with CCs (CTIC, 2017). It is surprising that farmers in the United States reported that more knowledge of CC benefits and more information about CC species would be top influencing factors to take up CCs given that the farmer-driven research and knowledge-share program (SARE) has been established for 30 years and has spent many years researching CCs and other sustainable ideas with farmers (Groff, 2015). Additionally, the USA continues to produce a vast amount of CC research compared to the UK and has a well-established extension network disseminating results.

The effect of CCs on soil quality and how to measure this may require specialist equipment that is only readily available to scientific research trials, although there are methods available to quickly and easily measure some soil quality indicators on farm. It is going to be vital to educate farmers in appropriate methods to assess soil quality indicators, given that the U.K. government intends to put ‘bold new measures to protect and restore soil health’ at the heart of a forthcoming agricultural bill (Downing & Coe, 2018). Methods such as the visual evaluation of soil structure (VESS) (Guimarães et al., 2011), the visual soil assessment (VSA) (Shepherd, 2003) and earthworm sampling (Open Air Laboratories (OPAL), 2016), are currently available and have been demonstrated to farmers. Additional methods such as water infiltration and slaking tests could also be carried out on farm (NRCS East National Technology Support Center et al., 2011). However, these methods will need validation, promotion and demonstration in the UK similar to methods already demonstrated (VESS, VSA and earthworm sampling) under projects such as ‘GREAT SOILS’ (AHDB, 2018) and ‘Ploughing on regardless’ (UK Research and Innovation, 2018). The survey results also highlight that the greatest uncertainty for on-farm measurement is the evaluation of organic matter and nutrient availability; ranked number 1 and 2 by soil health experts as the key indicators of soil health (Soil Security Programme, 2016). These two key indicators of soil health are often measured in the laboratory. However, the development of fast and affordable in field methods for assessing these important soil quality indicators would help ensure that farmers are equipped to measure and monitor their soils as part of the 25 year plan to improve the environment (DEFRA, 2018a).

3.5.7 Implications for Policy Makers

Recently the Secretary of State for DEFRA, in view of creating a new agriculture policy, announced that public money should be for public goods and ensure a natural capital approach for land use and management. CCs can achieve public goods, such as prevention of soil loss due to erosion (Posthumus et al., 2015), reduce nitrate leaching (Cooper et al., 2017), sequester carbon (Poeplau & Don, 2015) and improve biodiversity (Prechsl et al., 2017) as well as form part of a farming system that is less reliant on manufactured fertilisers, herbicides and fuel. As UK farmers and researchers develop a greater understanding of the use of CCs that have benefits on farm, but also perform important ecosystem services, attention may turn to how to subsidise CC use. If so, how would a CC be judged and what would be the requirements for receiving such financial assistance?

The EFA guidelines (Rural Payments Agency, 2016) for CCs need to be amended according to 71% of the respondents currently using CCs. A further 20% of respondents not currently using CCs indicated that a change in the species of CCs permitted under EFA would influence their decision to implement CCs.

Current guidelines require that CCs must be a mixture, which can add stability and resilience to a CC from weather and management decisions (Measures, 2015). However, in some instances a CC mixture does not deliver more ecosystem services than a single species CC (Finney & Kaye, 2017). A single species CC may be easier to manage, especially on organic farms or if it is sown as a companion crop (i.e. with maize) to then become an over winter CC.

Perhaps whether the CC is a single or mixed species should not be the first priority of a policy, but rather attaining and maintaining green cover, even if it is a single CC species, over a certain period of time. A tax credits program in the USA that supports the use of CCs (including single species) to reduce water and wind generated erosion requires that 60% land cover must be achieved by autumn and maintained over winter but can then be harvested or grazed in the Spring (Virginia Department of Conservation and Recreation, n.d.). Similar requirements in the UK would go some way to creating a CC policy that is more flexible and helps account for climatic, rotation, geographical and soil type differences between farms. A revision of policy regarding CC use would further encourage their use on farms, not only to the benefit of the farmer but also to help deliver ecosystem services to surrounding communities.

3.5.8 Limitations of the Survey

The survey used 117 responses in total which allowed trends and themes in the use and management of CCs in the UK to be identified. This only represents 0.19% of the 63,000 agricultural holdings in the UK that would fulfil the arable criteria (Armstrong, 2016; DAERA-NI, 2017; DEFRA, 2018c; Scottish Government, 2017). The USA survey had a similar response rate of 0.61% that would fulfil the equivalent criteria of agricultural holding type (USDA, 2014). The use of social media and the author's personal account (previously tweeting about CCs), to distribute the survey may have introduced bias in the demographic of the farming community that responded to the survey. If the survey was repeated alternative and additional platforms for advertisement and distribution should be considered to appeal to a wider audience. Furthermore, the number of questions should be reduced as this may help to increase the completion rate of the survey.

4 COVER CROPS FOR TIMELY NITROGEN MINERALISATION AND SOIL MOISTURE MANAGEMENT

4.1 Abstract

Cover crops (CC) can be utilised to reduce soil nitrate leaching. However, depending on species grown and CC termination management this may lead to nitrogen (N) immobilisation and/or depletion of soil water available to the following cash crop. Following wheat harvested in August and prior to forage maize planted in May, a multi-species frost sensitive CC was established in 2016 and repeated again in 2017. The effect of CCs on soil moisture was investigated in both years, with soil available N studied in 2017. The CC (black oats, oilseed radish and white mustard) was compared to a wheat stubble control, which subsequently grew with wheat volunteers over the 8 month trial period. In two contrasting seasons the results showed that the CC treatment, despite a significantly greater aboveground biomass, did not significantly affect the soil moisture at 0.1, 0.2 and 0.3m depths when compared with the control. The frost sensitive CCs were partially controlled by the cold temperatures and this resulted in a release of N into the soils from December to February before a second N-uptake event in March. This work found that i) the large biomass multi-species CCs did not utilise soil moisture differently when compared to the small volunteer wheat biomass in the control ii) frost sensitive CCs do not reliably senesce in temperate climates and iii) the significantly greater available soil N released in January due to the senesce of the frost sensitive multi-species CC would be more suitable for earlier sown spring crops (wheat / barley) than maize where, in a wet Spring, leaching may become a risk until its establishment in May.

4.2 Introduction

Cover crops (CC), are unharvested crops (but may sometimes be grazed) that are established between periods of cash crop growth and are utilised to concurrently enhance soil physical, biological and chemical quality indicators and associated soil functions. They have been used to alleviate the effects of soil compaction (Chen & Weil, 2010), prevent soil erosion (Blanco-Canqui et al., 2013; Posthumus et al., 2015), suppress weeds (Brust et al., 2014) and for carbon sequestration (Poeplau & Don, 2015). The use of CCs to improve water quality through the reduction of nitrate leaching (Cicek et al., 2015; Cooper et al., 2017; Justes et al., 2012; Macdonald et al., 2005; Plaza-Bonilla et al., 2015; Shepherd & Webb, 1999), and surface run-off and sediment loss (Korucu et al., 2018) is well documented. As well as the cost and time required to establish and manage CCs another barrier to their adoption is the perceived negative effect of CCs on the following cash crop. These include the immobilisation of nitrogen (N) via CC uptake and delayed availability, as well as soil moisture changes (too little soil moisture for crop growth or too 'wet' for crop establishment) (CTIC, 2017; Storr et al., 2019; White & Weil, 2010).

CC water use is reported to be 1.78 times greater than evaporative water losses associated with a no-till fallow (Nielsen et al., 2015a). Thus, CCs can potentially reduce soil water available at the time of cash crop drilling and early establishment. In the temperate climate of Serbia (annual rainfall of >600mm), it was reported that CCs reduced soil moisture prior to cash crop establishment (Krstić et al., 2018). Late termination of a CC also reduces soil water content following an over-winter CC of barley and vetch, although mulching of the CC residue led to greater soil water content than the fallow by the time of cash crop establishment (Alonso-Ayuso et al., 2014). In the Midwest, USA, it is reported that the growth of a rye (*Secale cerale* L.) CC over a 7 year period with variable rainfall/ temperature improved soil water storage and content, whilst during the drought of 2012 the CC was not detrimental to soil moisture conservation at 0.1 and 0.2m depths (Basche et al., 2016; Daigh et al., 2014). Under dry conditions, the FAO dual crop coefficient method indicates that CCs may reduce the deeper soil profile water status by 16% when compared to a fallow, though regularly distributed rainfall can replenish upper soil profile reserves (Bodner et al., 2007). Following CCs several years may be required to deliver beneficial differences to soil water availability, as time is required for the accumulation of organic matter and the improvement of soil structure through bioturbation. In the short term, (over one growing season) CCs have been shown to have no effect on soil moisture or water retention (Snapp & Surapur, 2018).

In a semi-arid environment the reduction of soil water from legume CCs resulted in decreased wheat yields (Nielsen & Vigil, 2005) whilst a cereal CC did not have a negative effect on crop yield (Basche et al., 2016).

The role of CCs in nutrient acquisition and recycling is well established (Komainda et al., 2016; Justes et al., 2012; Plaza-Bonilla et al., 2015; Couëdel et al., 2018; Baggs et al., 2000). However, there are difficulties in estimating when these nutrients, particularly N, are mineralized following the use of CCs (Snapp et al., 2005). Immobilisation of N following a CC can be detrimental to the following cash crop yield, with N contained within the CC biomass not released to match crop demand (Cicek et al., 2015). Ensuring synchrony between N release from the CC and N demand from the cash crop is dependent on a number of factors, including the C:N ratio. The C:N ratio is influenced by CC species, maturity and plant tissue as plant roots achieving a greater C:N ratio than the aboveground biomass (Kong & Six, 2010). A high or wide C:N ratio (>26) can result in net N immobilisation whilst plants with a low C:N ratio (<13) leads to net N mineralization (Justes et al., 2009). The timing and method of CC termination affects mineralisation with delayed CC incorporation reducing N mineralisation (Thorup-Kristensen & Dresbøll, 2010; Alonso-Ayuso et al., 2014; Poffenbarger et al., 2015). CCs terminated 2-3 weeks prior to cash crop planting may ensure a better synchrony between N mineralisation and the following cash crop’s N requirement (Ketterings et al., 2015; Crandall et al., 2005). However, early termination of the CC in spring may release N back into the soil at a time when it is susceptible to leaching before the cash crops are planted (Thomsen et al., 2016; Hu et al., 2018).

CC termination management is critical to the success of implementing CCs as this affects N mobilisation and ease of establishment of the cash crop into the remaining CC biomass (Radicetti et al., 2017). In the UK, the most commonly adopted practice for CC termination is the use of herbicide or mechanical incorporation with tillage (White et al., 2016; Storr et al., 2019). However, Glyphosate, a cost-effective herbicide used by many UK farmers to terminate CCs, only has a license to be used in the European Union until 2022 following a license extension granted in 2017 (European Commission, 2018). A frost sensitive CC was used in this study as a possible alternative CC termination method to remove the reliance on herbicide and tillage in CC management.

This study critically evaluates the effect of a frost sensitive multi-species CC on i) soil moisture at 0.1, 0.2 and 0.3m depths prior to cash crop establishment ii) the availability of N at 0-0.15m depth when compared to a naturally regenerated wheat volunteer control over the CC growing period.

4.3 Materials and Methods

4.3.1 Experimental Design and Site Characteristics

Two replicated field trials were established near Ely, Cambridgeshire on the edge of the lowland Fen. The first trial was conducted at Prickwillow from August 2016 – May 2017 and the second trial, a repeat of the first trial, took place on a nearby field at Littleport from August 2017 - May 2018. Both sites have the same soil type (Drainic Sapric Histosol (IUSS Working Group WRB, 2015) although the organic horizon in some places is *circa* 0.4m depth indicative of a Mollic Gleysol. Organic matter in the top soil was 25 and 27% w/w for the sites at Prickwillow and Littleport, respectively. Both trials took place on a large commercial farm (>5000 ha) with all field operations carried out by the host farm and subject to commercial pressures and considerations. The CC was implemented between wheat and maize crops.

At Prickwillow, following wheat harvest on 14th August 2016 and a uniform application of anaerobic digestate liquor (40 m^3 ha^{-1}) the frost sensitive CC treatment (Table 4.1) was sown with a Horsch Sprinter ST drill on the 26th August 2016. Control plots comprised zero intervention and thus natural vegetation regeneration (wheat volunteers) occurred over the trial period. The CC treatment and the control consisted of 9 plots (12m x 24m) across the trial field. The field was desiccated with glyphosate on 7th April 2017 and forage maize was established with a Pöttinger Aerosem 3002 ADD drill on 11th May 2017.

Table 4.1: Table of cover crop species

Frost sensitive CC treatment (25 kg Ha^{-1}) £42 ha^{-1}
60% Cadence black oats (*Avena stigosa* cv. Cadence)
35% Final oil radish (*Raphanus sativus* cv. Final)
5% Braco White mustard (*Sinapis alba* cv. Braco)

At Littleport the same CC treatment (Table 4.1) was sown in triplicate with a control (natural vegetation regeneration of wheat volunteers). The CC was established on the 24th August 2017 following wheat harvest on the 12th August. The trial was desiccated using glyphosate on the 21st April 2018 prior to establishment of forage maize (P8200) on the 20th May 2018. Plot size was 24m x 80m, with 3 replicates of each the control and CC treatment, which alternated across the field. Due to logistics, rotational context and supply no anaerobic digestate liquor was applied at the Littleport trial.

In both years the trial plots received the farm standard agronomic interventions associated with maize nutrition and fungicide applications. At the Littleport trial herbicide was applied during maize growth. This was not compatible with the Prickwillow site as companion crops were established with the maize on other areas of the field as part of another trial.

4.3.2 Soil Moisture and Nitrogen Determination

Volumetric soil moisture was determined at 0.1, 0.2 and 0.3m depths using a PR2 profile probe (Delta T, Burwell, UK). Measurements were taken at 6-8 day intervals from January until May in both trial years (Qi & Helmers, 2010). Soil moisture access tubes were installed 3 weeks prior to the collection of data to allow the soil to settle around the access tube. At Prickwillow, soil moisture access tubes were installed in 6 of the 9 plots for the control and frost sensitive plots. At Littleport there was an access tube per plot of the control (n=3) and CC treatment (n=3). Soil moisture was measured in 2017 and 2018 at Prickwillow and Littleport, respectively. At Prickwillow, only soil moisture was measured. These two locations are approximately 9km apart. .

At the Littleport trial site, three sub-samples of soil (0- 0.15m depth) were taken and combined for each plot for the determination of available-N: N-NH_4 and N-NO_3. Cooper *et al.,*(2017) took top soil samples at 0-0.15m depth for NO3 – N and other nutrient analysis alongside a comprehensive set of measurements to depth (0.9m) and the use of porous pots to measure leaching through the soil profile. Specific measurements for N leaching were not taken in the presented study and thus the leaching potential of treatments in this study is only inferred from the data collected at 0-0.15m.The fresh soil samples were stored at <4°C before sieving to <5.6 mm and extraction with 2M KCl (1:5 soil to solution ratio) and analysis using the Burkard SFA-2000 segmented flow. Henceforth, available-N refers only to N-NO_3, as the level of N-NH_4 was 0 mg Kg^{-1} soil.

Aboveground biomass was determined from a 0.25m^2 quadrat, with one sample taken per plot and mean averaged across the CC treatment and control. Belowground biomass, was determined from five plant roots per plant species, to 0.15m depth using a bi-partite root corer of 0.08m diameter (Eijkelkamp, The Netherlands). The roots extracted in the cores were then thoroughly washed using tap water. Plant material (above ground biomass and root samples) was dried at 65°C and weighed. Total C and N were determined using an Elementar Vario III. The data obtained was used to calculate the C:N ratio and nitrogen present in the aboveground and belowground biomass.

Nitrogen contained within the plant root was determined as follows: Three plant establishment counts were conducted in each plot using a 0.25m^2 quadrat and median averaged for each plot. Treatment plant count averages were then calculated using the mean. Root biomass N per species was calculated using equation (4-1).

$$\frac{plant\ Est.Count}{Ha}\ x\ Dried\ Root\ Mass\ (kg) x\ Root\ N(\%)\ = kg\ N\ ha^{-1} \quad \textbf{(4-1)}$$

For the CC treatment individual plant species were summed.A weighted average of CC root C:N ratio was calculated using the average C:N ratio of an individual plant species (n=5) and, calculated by plant counts, was weighted by its proportion present in the mixture. Calculation of the root C:N ratio produced 3 replicates for the cover crop treatment with 3 different establishment ratios but no replicates were possible for the control (wheat volunteers), as all had a ratio of 1. Thus, no statistics were used to described the root C:N ratio.

4.3.3 Determination of Maize Yield

For the CC treatment and control maize yield was determined by weighing 2 rows of 10 plants and extrapolated to fresh weight (t ha^{-1}). Plants were cut at a height of 0.22m to replicate forage harvesting and weighed in the field to 0.1Kg. Three randomly selected maize plants from each treatment were then dried at 65^{o}C for 48 hrs to determine dry matter content. Maize yield was determined on the 4th October 2017 and 3rd October 2018 for the trials at Prickwillow and Littleport, respectively

4.3.4 Statistical Analysis

Soil moisture data was screened for erroneous results that were likely produced by air pockets surrounding the probes sensors. All data taken per time interval and depth was used to determine the mean and standard deviation, data falling above and below 2 standard deviations from the mean were excluded. Data was then sense-checked and compared to field notes to remove data points that were affected by soil cracks that appeared near to the soil moisture access tubes. As the PR2 profile probe recorded a measurement at 120° intervals per depth, the measurements were mean averaged per depth for each installation point. Data was analysed using a T-test to a 0.05 probability level in Excel.

4.3.5 Climatic Conditions During Field Trials

Weather stations were located at both field trial sites. The weather stations (Pessl Instruments) were operated by a third party (FieldClimate) on behalf of the farm and the data was made available to the author. Potential soil moisture availability, the difference between daily cumulative rainfall and evapotranspiration (both measured by the weather station) is shown in Figure 4.1 with the assumption that the soil is at field capacity on 1st February in the preceding year of taking soil moisture measurements. Spring 2017 was extremely dry when compared to spring 2018 with 64.8 and 180.8mm of rain, respectively between March and May. The 30 year average rainfall in Eastern England between March and May is 145.5mm (Met Office, 2018).

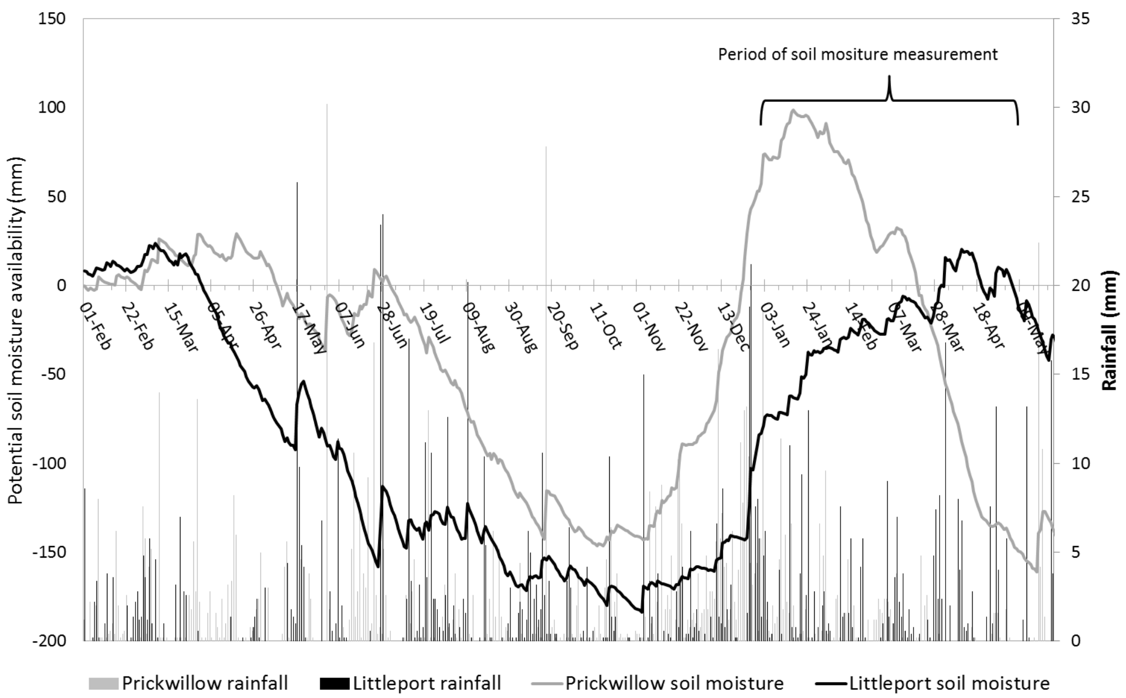

Figure 4.1: Potential soil moisture availability (mm) and rainfall at the trial sites.

4.4 Results

4.4.1 Effect of CC on Volumetric Soil Moisture

The volumetric soil moisture content (%) in both years across all sampling points during the CC growth period was not statistically different between the CC and control treatments at the 0.1, 0.2 or 0.3m soil depth (Figure 4.2). The prevailing weather conditions appear to have the greatest influence on soil moisture content and there was no significant treatment effect. This is highlighted by the response of soil moisture to the dry spring conditions in 2017 (Figure 4.2 A, C & E). In Spring 2018, at Littleport, there was persistent rainfall over the measurement period and volumetric soil moisture remained at or near field capacity for all depths for both the control and CC treatments (Figure 4.2 B, D & F).

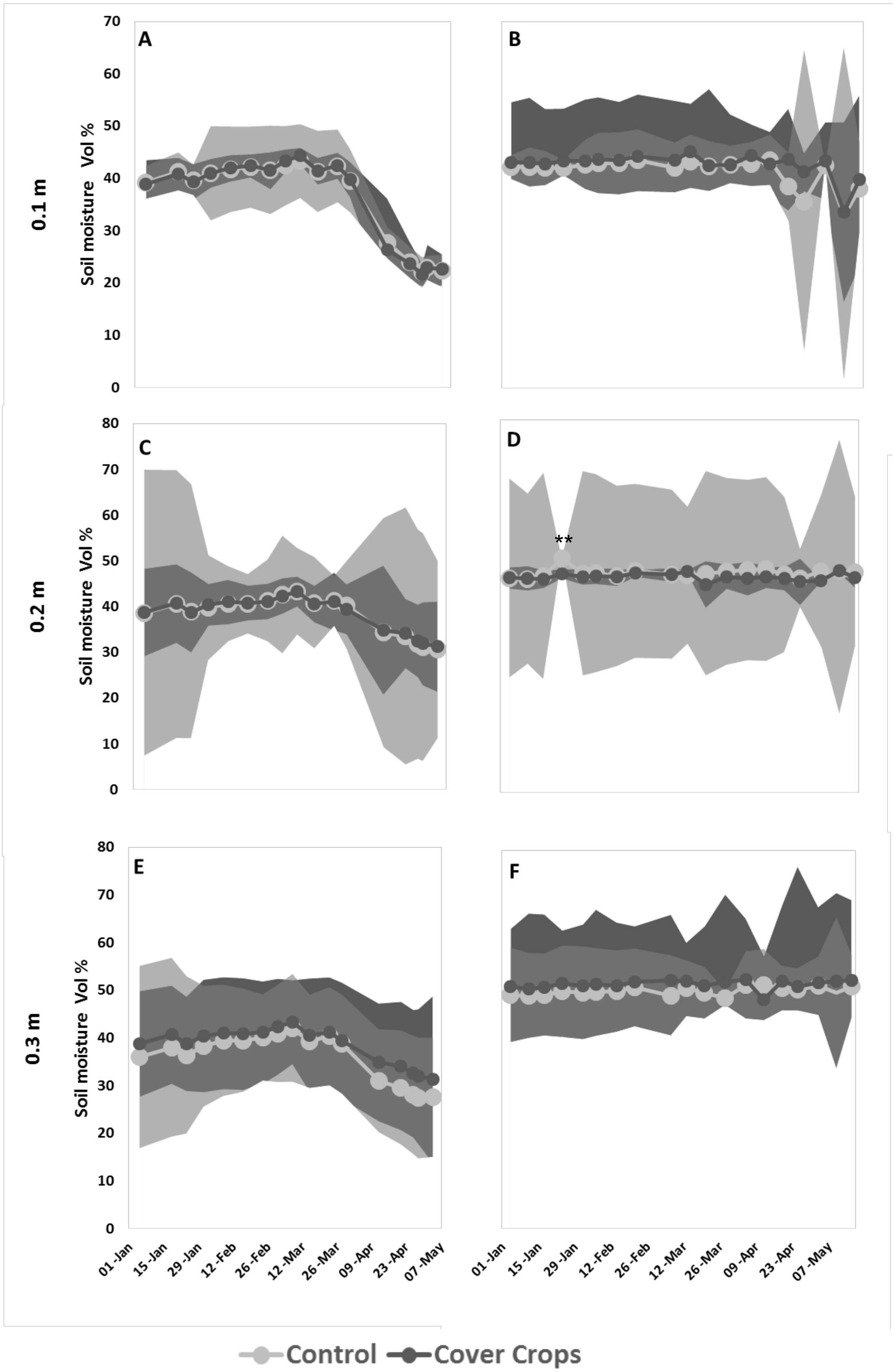

Figure 4.2: Mean soil moisture (Vol %) at 0.1, 0.2 and 0.3m depths at Prickwillow (A, C, E) and Littleport (B, D, F), respectively. Statistical significance is denoted by ** (T-Test; p<0.05). Shaded area indicates SEM. n = 3, unless data points were removed by the data screening process.

4.4.2 Cover Crop Aboveground Biomass

At the Littleport trial site, CC growth was rapid after establishment and approximately 3 months after establishment achieved a maximum, significantly greater biomass than the control on 21st November 2017 (Figure 4.3). From the end of November onwards there was a decrease in above ground biomass as the frost sensitive CC species senesce. Aboveground biomass of the CC treatment stabilised for the remainder of the trial period at ≈ 2.5 t ha^{-1} before termination on 21st April 2018. Aboveground biomass was significantly greater in the CC treatment on 21st November 2017, 4th January, 14th February, 7th March and 12th April 2018.

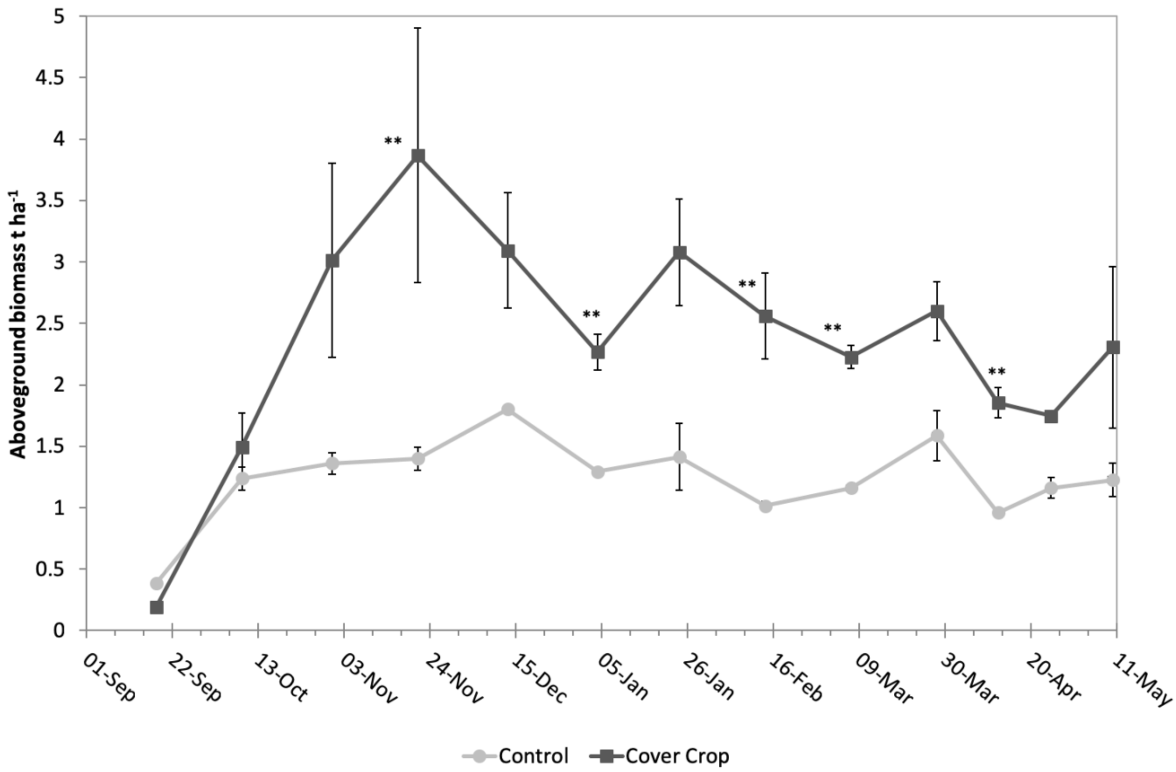

Figure 4.3: Dried aboveground biomass measured between September 2017 and May 2018 at Littleport. N = 3, error bars = standard error of the mean (SEM). Statistical significance is denoted by ** T-test (p <0.05).

4.4.3 Effect of Cover Crop on Nitrogen Dynamics

Figure 4.4 highlights the soil available N dynamics over the Littleport trial site 2017-2018 CC growing season. Initially, CCs rapidly depleted soil available N. However, by the 18th September the wheat volunteers of the control plot had significantly depleted soil available N when compared to the CC treatment. Soil available N increased following the senescence of the CC between December 2017 and mid-February 2018. A decrease of soil available N occurred from February 2018 until the end of April 2018 and finally there was a large increase in soil available N on the last sampling date in May following CC termination (21st April 2018 again). From December 2017 onwards soil available N was greater (t-test p= <0.05, <0.1, Figure 4.4) in the CC treatment, and significantly so on several occasions, when compared to the control.

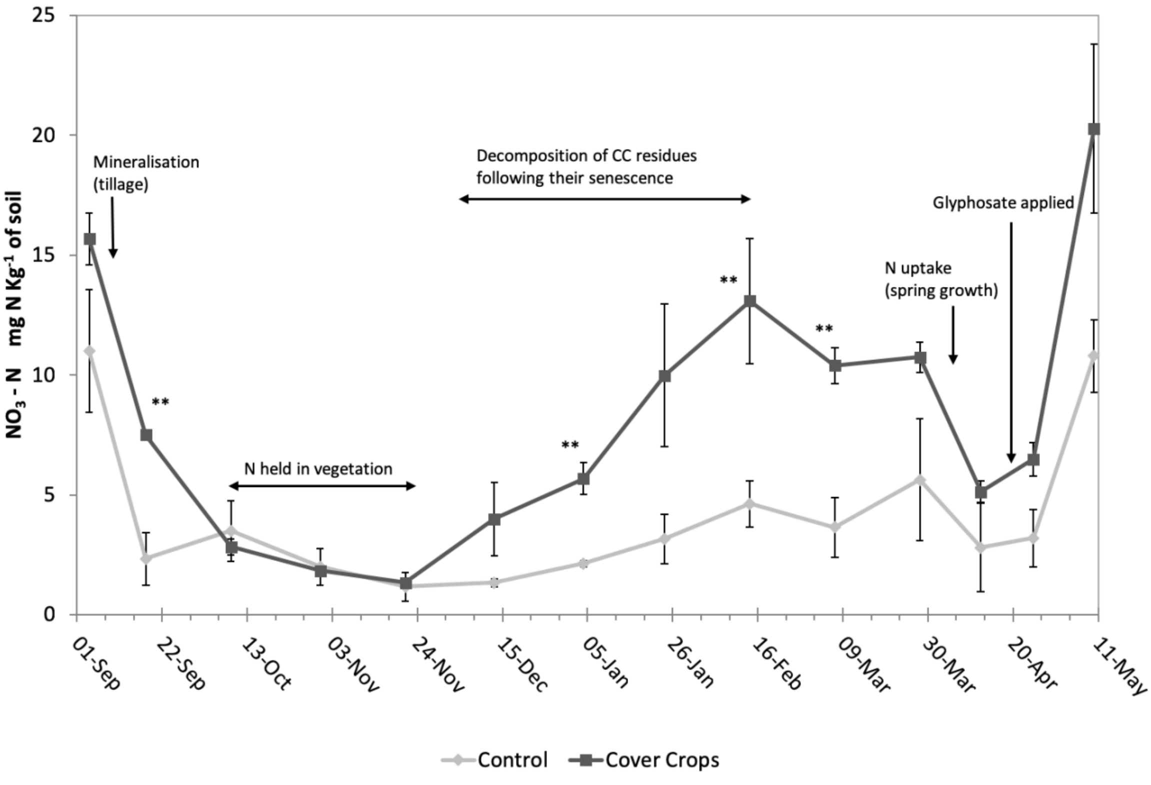

Figure 4.4: NO_3-N measured between September 2017 and May 2018 at the Littleport trial. N = 3 per treatment, error bars = SEM. Statistical significance, T-test (p <0.05), is denoted by **.

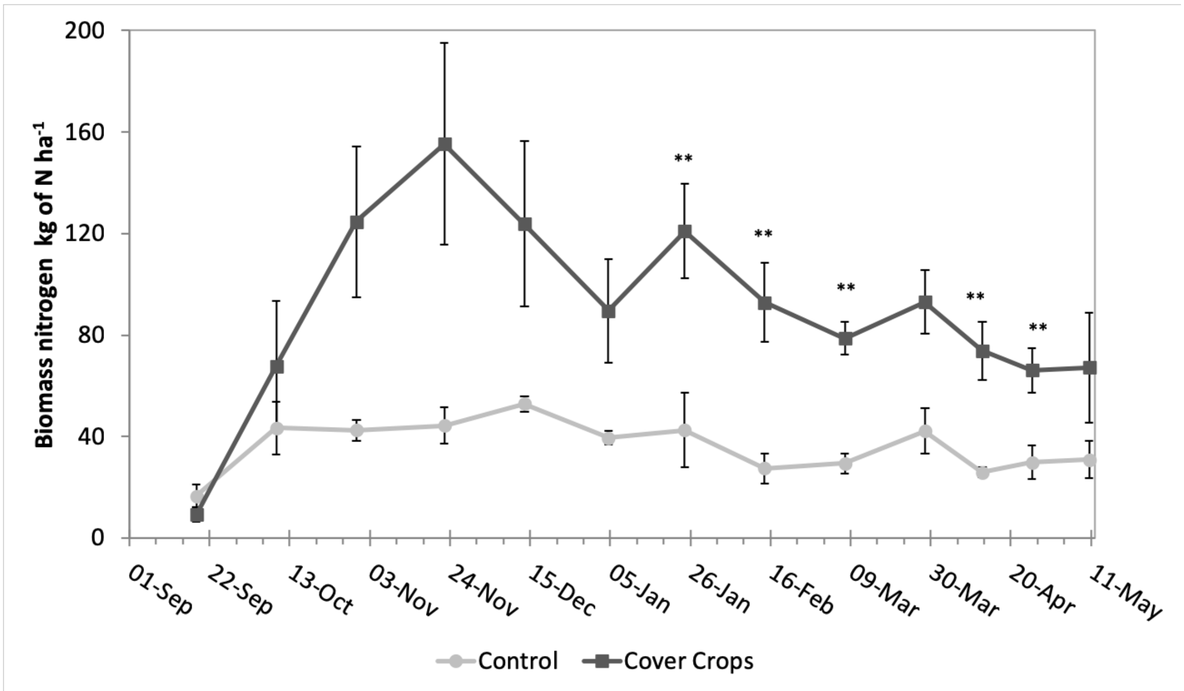

Figure 4.5: Aboveground biomass N (kg ha^{-1}) measured between September 2017 and May 2018 at the Littleport trial. n = 3 per treatment, error bars = SEM. Statistical significance in is denoted by ** T-test (P<0.05).

Figure 5 shows the increased N held within the CC biomass as compared to the control treatment (N in the wheat volunteers), this was significant for the latter period of the trial (end of January 2018 to May 2018). Root biomass N content measured on the 22nd November 2017 (peak aboveground biomass) was significantly different between the control (mean = 8.7 kg of N ha^{-1}, SD =1.4) and the CC (mean = 17 kg of N ha^{-1}, SD = 1.3) treatment; (t (4) = 4.42, p = 0.012).

From the 7th March 2018, the C:N ratio in the CC biomass was significantly lower than the control (wheat volunteers) (Figure 4.6). In both treatments the C:N ratio increased throughout the sampling period. Using plant data collected on 22nd November 2017, root C:N ratio was calculated as 19 and 21 for the cover crop treatment and wheat volunteers of the control, respectively.

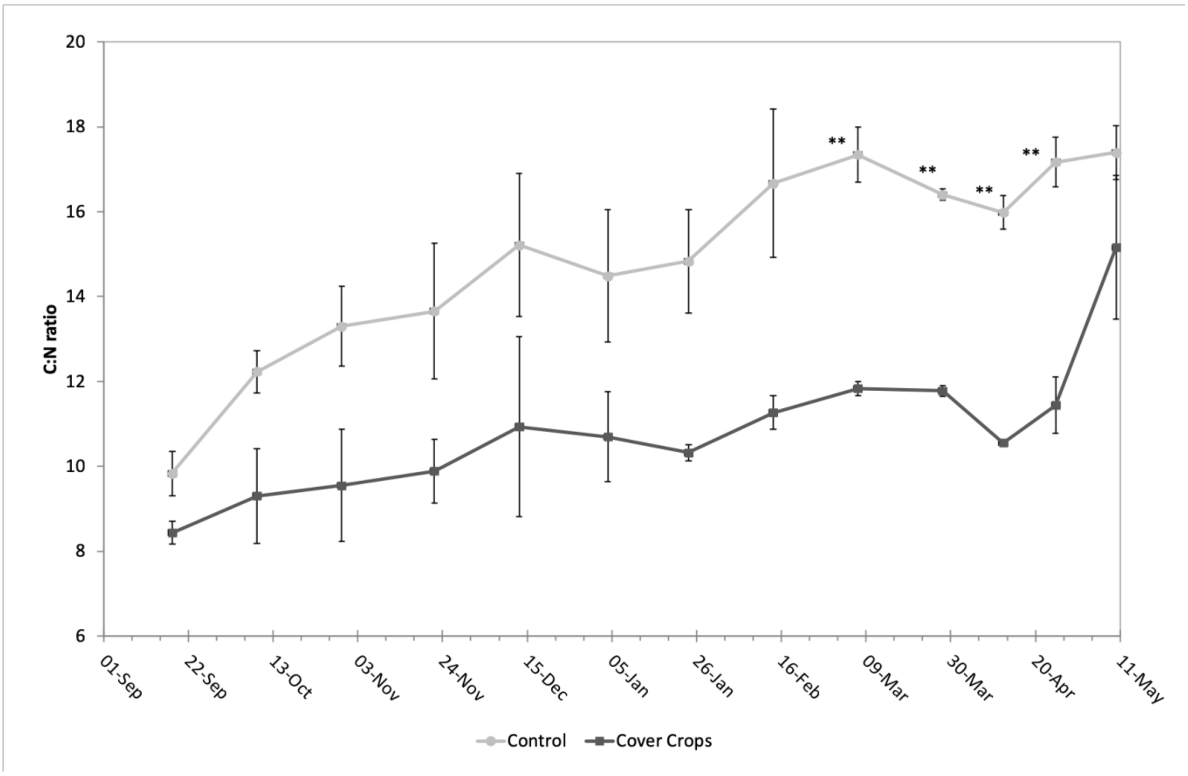

Figure 4.6: Aboveground biomass C:N ratio. n = 3, error bars = SEM. Statistical significance, T-test (P<0.05), is denoted by **.

4.4.4 Maize Yield

There was no statistical difference between the maize yield (DW) following the CC treatment and the control (t test $p > 0.05$) (Table 4.2). Maize was harvested at a dry matter of 29 and 40% at Prickwillow and Littleport, respectively.

Table 4.2: Mean maize yield t ha^{-1}. SEM is shown in parentheses.

Treatment	Prickwillow 2017 (n=5)	Littleport 2018 (n = 3)
Control	69.2 (3.5)	30.6 (0.5)
Cover crops	69.7 (1.2)	36.0 (16.3)

4.5 Discussion

4.5.1 Volumetric Soil Moisture Content

Some farmers have concerns that CCs may use too much soil moisture and reduce the amount available to the following cash crop (Conservation Technology Information Center, 2017; Storr et al., In Press). American research reported that CCs can reduce soil moisture (Nielsen et al., 2015a), have no effect (Daigh et al., 2014; Snapp & Surapur, 2018) or can improve soil moisture availability (Basche et al., 2016). In high rainfall years, CC residue may maintain soil moisture, which could make establishment of the next crop difficult. Some farmers are concerned with CCs becoming a hindrance to cash crop planting by reducing soil moisture evaporation; this leaves soils too wet and not conducive to effective drilling of the cash crop (White & Weil, 2010). Contrasting trial years, with respect to rainfall pattern and soil moisture availability (Figure 4.1) presented in this study allow the two scenarios of a wet or dry CC period to be compared. The data presented in Figure 4.2 suggests that there is no significant difference between the CC treatment and control in both 2017 (dry spring) and 2018 (wet spring) at depths of 0.1, 0.2 and 0.3m.

Several factors may explain the lack of difference in soil moisture between the CC treatment and the control. Firstly, had the CC with its significantly greater aboveground biomass (Figure 4.3) used a considerable amount of soil moisture over the autumn (prior to the soil moisture measurement period) then it is possible that the over-winter rainfall in both years was able to replenish soil moisture levels. Generally, in the U.K. soils are at field capacity between October and February/March, as evapotranspiration is minimal during this time due to limited plant growth, soil cover and low temperatures. Basche *et al.,*(2016) reported that, from 7 seasons of trials Iowa, U.S.A, rainfall usually replenished the soil moisture that was transpired by a single species rye CC; with CCs, typically, only using 5% of the annual precipitation (average rainfall of Iowa is 847 – 1186mm). Even if soil moisture was reduced during CC growth due to transpiration, the effect appears to be quickly diminished by sufficient autumn/winter rainfall (Martinez-Feria et al., 2016). Furthermore Nielsen *et al.,* (2015a) concluded that a single species CC does not use water any differently than a mixed species CC. The wheat volunteers present in the control treatment would be comparable to a single species CC, and thus have a similar effect on soil moisture as the multi-species CC utilised in this study. A combination of these factors may explain the lack of difference between soil moisture for the CC treatment and the control for both years. Overall, soil moisture is not significantly reduced by the presence of a multi-species, frost sensitive CC when compared to a control that subsequently grew wheat volunteers of a significantly lower biomass.

4.5.2 Soil Available Nitrogen

CCs are effective scavengers of soil N and thus reduce the possibility of N-leaching over winter (Cooper et al., 2017). However as the nitrogen is contained within the plant tissue of the CC, it's availability to the following cash crop may be compromised and subsequently have a negative effect on growth and yield of the following crop. The CC species selected were all frost sensitive and the study quantified the presence of N in the soil during their growth and senescence – which would be unpredictable and gradual. With frosts expected from mid-November onwards in the U.K. climate, these CCs may reduce N immobilisation.

Initially, there is an increased amount of N in the CC treatment which may be due to N mineralisation caused by the disturbance of the drill coulters when establishing the CC. This disturbance led to a greater soil N availability in the CC treatment on the first two sampling dates before parity between the CC and wheat volunteer control is reached on the third sampling date. Both the CC and control result in an initial (1st September – October 13th 2017) rapid decline in the availability of the soil N (Figure 4.4).

During October and November 2017, similar available soil N concentrations were evident between the control and CC treatments, suggesting that despite the large difference in aboveground biomass between the wheat volunteers of the control and the CC treatment (Figure 4.3), that wheat volunteers are equally as effective as the CC at N-uptake in the topsoil to 0.15m depth. This agrees with the previous work of Baggs *et al. ,*(2000) who found that naturally regenerated vegetation in a fallow treatment were as effective as the CC species investigated at reducing NO_3 –N over winter. However, naturally regenerated fallows may also increase weed prevalence (Baggs et al., 2000) – this would be undesirable in wider farm management objectives. Growth of wheat volunteers could act as a green bridge, hosting pests and disease capable of infecting adjacent cash crops (Suffert et al., 2011).

Despite a poor frost kill of the CC in the winter, soil available N increased in the CC treatment between December 2017 and March 2018. This may aid establishment and growth of the following crop as the early decomposition of the CC residue led to elevated soil N content, minimising the risk of N immobilisation at the time of establishment for spring crops. However, nitrate leaching could be a risk over the remainder of the winter and early spring (especially in wetter years) should the following cash crops not be planted early enough to take up the N and the soil hydrological conditions permit leaching through the soil profile (Dean & Weil, 2009). In this study, the next crop was maize, planted in May, so in very wet springs there is a risk that the increased soil N could be leached below the rooting depth of maize. Leaching of N would be less of an issue for earlier planted spring crops such as spring wheat/ barley that are planted from the beginning of March onwards. It has been shown that so long as a minimum biomass can be maintained (0.9 – 1.5 t ha^{-1}), then leaching can be reduced sufficiently (De Notaris et al., 2018). The trial shows that there was a reduction of soil available N between mid-February and mid-April. During this time it was observed that there was regrowth in the CC (oilseed radish in particular) and wheat volunteers. The wheat volunteers in CC treatment and control and regrowth of the CC species may be sufficient to prevent significant leaching. Following the application of glyphosate to the trial area, there is a rapid increase in soil available-N in the CC plots. This can be attributed to the decomposition of CC residues but possibly glyphosate itself. Following application, glyphosate, with a C:N ratio of 3:1, is directly mineralised by the soil microorganisms which increases N (and C) mineralization (Haney et al., 2000).

The final sampling taken in May 2018 shows the rapid and significant increase in soil available-N present in the CC plot resulting in a greater quantity of soil available N when compared to the initial measurement taken in September 2017. This increase of soil available-N at 0-0.15m depth may result from the uptake of N from deeper depths by the CC roots and reallocation to the upper profile following decomposition of the CC biomass. Radish roots have been shown to grow to depths of 2.5m in 2 months and are able to take up considerable NO_3-N depleting the soil of potentially leachable NO_3-N (Kristensen & Thorup-Kristensen, 2004). Whilst leaching of N through the soil profile will be a concern following the senescence of the frost sensitive CC, there could be benefits of frost termination with i) earlier N availability for the following cash crop aiding establishment and growth and ii) reduced reliance on herbicide or tillage as a means to terminate CC biomass, as some of the biomass is partially controlled by the cold temperatures.

4.5.3 Cover Crop Biomass Nitrogen and Carbon:Nitrogen

Above ground biomass-N and root-N concentrations are significantly higher in the CC treatment compared to the control (Figure 4.5), suggesting that a greater quantity of potentially leachable soil N has been retained in the CC plant tissue. Brassica species have rapid root growth that is able to scavenge and deplete soil available-N throughout the soil profile (Thorup-Kristensen, 2001a). Despite the increase of the soil available-N following CC senescence from December to March (Figure 4.4), Figure 4.5 shows that the CCs still contained approximately 1/3 of the N it had accumulated at peak biomass, which is approximately double the amount of N contained in the wheat volunteers of the control plot. This suggests that the CC, although partially terminated by the frost over winter, still retained N throughout the spring (reducing potentially leachable N) when compared to the control that naturally regenerated with wheat volunteers.

Such is the efficiency of the CC roots scavenging ability, the C:N ratio of the CC aboveground biomass (range = 8-14) is comparable to that of legumes crops (range = 10-15) (Couëdel et al., 2018). Following termination (21st April 2018), the CC treatment and wheat volunteers of the control had an intermediate C:N ratio of between 14 and 18 for the aboveground biomass. The C:N ratio of the CCs is lower than the control, thus it would be expected that the N would be mineralized in the CC treatment quicker than the control. The C:N ratio of the roots is greater than it's aboveground biomass by 62 and 90% for the control and CC treatment, respectively. Generally, roots when compared to shoots have a higher lignin-suberin content, which leads to slower N mineralisation (Abiven et al., 2005; Hu et al., 2018). The recalcitrant carbon compounds present in the roots lead to a greater residence time in the soil (≈2.4x) compared to carbon present in the shoot material, thus making a greater contribution to soil organic carbon (Kong & Six, 2010; Rasse et al., 2005). The greater C:N ratio of the roots (19 and 21 for the CC treatment and control, respectively) can initially lead to net N immobilization, followed by net N mineralisation several weeks later (Justes et al., 2009). The faster N mineralisation of aboveground biomass is complimentary to the slower mineralisation of the belowground biomass. Slower root decomposition would provide N at a latter growth stage of the following crop, whilst the quicker mineralisation of CC aboveground biomass provides N earlier to the following crop supporting its establishment. Additionally, with the aboveground biomass mineralised quicker this is likely to benefit subsequent drilling operations, as residue is less likely to impede drill coulters and affect seed placement/ tangle the machine.

Finney et al., (2017b) report that 'there is a central trade-off between biomass services (biomass production, N retention & weed suppression) and nutrient services (N supply, cash crop production and profitability)'. Therefore, a compromise in the management of CCs will be needed to ensure that the following cash crop is not disadvantaged through N retention by the CC. Additionally, there is a possible trade-off between termination techniques used to control CCs. This research used frost sensitive CCs to assess the feasibility of eliminating or reducing the need for glyphosate to facilitate termination. Glyphosate is cheap and commonly used to terminate CCs but is only licensed for use until 2022 (European Commission, 2018) and if the license is not renewed farmers will need to find alternative methods for CC termination. This research indicates that frost sensitive species and varieties cannot be reliably terminated by the frost in East Anglia. However, further north in the U.K. frosts are likely to be more severe and dependable resulting in a more reliable termination of frost sensitive CC species. Alternative methods for CC termination such as tillage (although not practised in all farming systems), roller crimping (currently unreliable and not well developed in Europe (Peigné et al., 2015) as well as flailing, grazing or perhaps different herbicide control options will need to be investigated. Grazing and roller crimping will also increase the trafficking of the field, which may increase soil compaction if under taken when the field is ‘wet’. Further investigation of CC species and varieties would allow better characterisation of their traits so selection can be better matched to the aims of management and ecosystem services.

4.6 Conclusion

This study showed that prior to maize establishment CCs did not affect soil moisture at 0.1, 0.2 and 0.3m depths when compared to the control, despite significant differences in aboveground biomass. The control, which grew with wheat volunteers, was also as effective as the CC at reducing soil available N present in the peat topsoil at 0-0.15m. The control reduced soil available N throughout the duration of the trial when compared to the CC treatment. However, the use of frost sensitive CCs, despite poor frost termination control, permitted the early decomposition of CC residues and thus significantly increased (180%) the soil available-N present in mid-February. This may have benefits for earlier sown spring cereals such as wheat and barley. But for later sown crops, such as maize, nitrate leaching may be a risk in a wet spring and will require further research. The trial highlighted the unreliability of complete CC termination that is reliant on frost for the CCs and varieties evaluated.

5 LIMITED EFFECT OF COVER CROPS ON SOIL STRUCTURE IN THE SHORT TERM

5.1 Abstract

Cover crops (CC) alter soil structure directly through root growth and their contributions to soil organic matter. This research investigated the effect of CCs on soil structure when planted in two CC periods i) between wheat and maize and ii) between maize and lettuce. CCs were zero till established following wheat harvest and their effect on soil structure assessed the following spring. Maize was then established with a companion crop, which remained until the spring after maize harvest. Between wheat and maize, cereal and brassica based CCs were established. Then a tall fescue and white clover companion crop was sown with the maize. Following the first CC between wheat and maize, there was no significant difference in the visual evaluation of soil structure, bulk density or shear strength. However, in one of two years, following the CC soil penetrative resistance was significantly increased at 0.08-0.12m soil depth when compared with the control. After the addition of the companion crop with maize, there were isolated significant differences in soil penetrative resistance. Furthermore, bulk density and shear strength were significantly reduced at 0.05 and 0.15m depth, respectively. There was no effect on lettuce head mass following the treatments.

5.2 Introduction

Cover crop (CC)s are sown between cash crops in arable rotations and through the creation of biopores and the return of organic matter can enhance soil function (e.g. water and nutrient cycling) which benefits the ecosystem services provided by soils. CCs are effective scavengers of potentially leachable nitrogen (Justes et al., 2012), can suppress weeds (Osipitan et al., 2018), increase soil organic carbon (Poeplau & Don, 2015), alleviate the effects of mild soil compaction (Chen & Weil, 2011) and benefit soil structure (Stobart et al., 2015).

Soil compaction is a global problem and is one of the main threats to soils in the U.K (DEFRA, 2009a). Soil compaction is partly a result of the increased size and mass of farm machinery used in modern agriculture and is further exacerbated by the need to harvest crops in sub-optimal conditions (soil is too 'wet') to fulfil the orders of food supply chains (Blanco-Canqui et al., 2015). As well as impeding root growth and access to nutrients, compaction can create a water logged, anaerobic environment, all of which reduce plant productivity (Batey, 2009) and wider ecosystem services such as flood management (Gregory et al., 2015). Wheat yield losses of up to 2.42 t/Ha have been recorded for each 1 MPa increase in soil strength (Whalley et al., 2006).

CCs are able to impart changes on the soil structure through root growth and accumulation of biomass. Biodrilling, the creation of pore space in the bulk soil from CC root growth (and/or the presence of soil fauna) creates pathways of least resistance for the roots of the following cash crop (Cresswell & Kirkegaard, 1995). These biopores may permit the preferential growth of the following crop's roots in search of nutrients and water in the subsoil (Williams & Weil, 2004). Different root architectures of a CC lead to differences in soil pore size and can subsequently affect the spatial root distribution of the following crop (Burr-hersey et al., 2017; Han et al., 2016).

Secondly, CCs are a source of organic matter that is returned to the soil. Both above and below ground crop biomass make valuable contributions to soil organic matter, which may become stratified through the soil profile under no-till farming practices (Abdollahi & Munkholm, 2014; Kay & Vandenbygaart, 2002;

Mazzilli et al., 2015). The majority of differences to soil quality indicators (total organic carbon, number of water stable aggregates, bulk density) occur in the 0-0.075m soil depth as opposed to deeper layers due to i) deposition of CC organic material and ii) greater root length density at or near the soil surface (Blanco-Canqui et al., 2011; Bodner et al., 2010).

CC species with a tap root such as brassicas can enhance biopore formation, which, when compared to fibrous roots, can alleviate the effects of mild compaction (≈2 MPa) by increasing maize root growth in deeper soil layers (Chen & Weil, 2011; Han et al., 2015a). Thicker roots are better able to resist buckling and can create a greater force to cause soil deformation in front of the root tip in higher strength soils (Materechera et al., 1992). The pore space created by the plants roots leads to reduced soil bulk density (Haruna & Nkongolo, 2015; Hubbard et al., 2013). However, a recent meta-analysis of the effect of CCs on soil quality indicators in the Pampas region concluded that CCs only resulted in 1% decrease in soil bulk density (Alvarez et al., 2017). Furthermore, when soil is assessed according to the visual evaluation of soil structure (VESS) (Guimarães et al., 2011) the use of brassica CCs in the UK resulted in an improved soil structure condition compared to a stubble (Stobart et al., 2015).

Limited information exists on the effect of CCs in the short term, especially in field trials on organic soils. Soil aggregate dynamics following CC growth and the effect of a change in bulk density on root architecture of different CC root species have been investigated recently in pot trials (Burr-hersey et al., 2017; Linsler et al., 2016). Assessment of soil physical quality indicators in field trials has led to conflicting results. CCs improved soil structure (VESS) when compared to a stubble control after one season (Stobart et al., 2015). But when using quantitative methods, such as penetrative resistance, bulk density or water aggregate stability, CC treatments did not significantly improve soil physical quality when compared to a bare fallow (Acuna & Villamil, 2014). Given the general lack of research and the inconclusive results so far, the aim of this study was to evaluate the ability of tap-rooted CCs followed by a companion crop to reduce soil compaction and improve soil structure in the topsoil (0-0.3m) over i) a short single CC period (8 months) and ii) CC followed by an over-winter companion crop sown with maize.

5.3 Materials and Methods

5.3.1 Field trial

The trial follows the rotation of wheat – maize – lettuce. CCs were established between wheat and maize (phase 1) followed by a companion crop which was established with maize and remained over winter following maize harvest (phase 2). Phase 1 CCs were assessed at two trial sites, Prickwillow (2016-2017) and Littleport (2017-2018) whilst phase 2 was only assessed at Prickwillow (2017-2018).

The trial sites are located near Ely, Cambridgeshire. Both sites have the same soil type (Drainic Sapric Histosol) although the organic horizon in some places is close to 0.4m (Mollic Gleysols). Soil characteristics of the trial sites are shown in Table 5.1.

Table 5.1: Soil characteristics of field sites.

Soil characteristic	Prickwillow	Littleport
pH	7.7	7.4
Total Carbon %	14.0	15.1
Total Nitrogen %	1.0	1.1
Soil Organic matter %	25.4	26.8

Phase 1 was established on 26th August 2016 at the Prickwillow trial site following wheat (*Triticum aestivum* cv. Skyfall) harvest and the uniform application of digestate liquor (maize feedstock) at 40m^3 ha^{-1}. In phase 1, at Prickwillow, two CC mixtures (Table 5.2) were zero till established using a Horsch Sprinter ST drill in triplicate with control plots that were 24m wide. Glyphosate (4 l ha^{-1}) was applied across the trial site on the 7th April 2017 to terminate wheat volunteers and any remaining CC plants.

Table 5.2: Cover crop species planted at Prickwillow, August 2016.

Frost sensitive mixture (25 kg Ha^{-1}) £42 ha^{-1}	Winter hardy mixture (30kg Ha^{-1}) £36 ha^{-1}
60% Cadence black oats	60% Protector forage rye
Avena stigosa cv. Cadence	*Secale cereal cv.* Protector
35% Final oil radish	30% Evergreen oil radish
Raphanus sativus cv. Final	*Raphanus sativus cv.* Evergreen
5% Braco White mustard	10% Berseem clover
Sinapis alba cv. Braco	*Trifolium alexandrium cv.*

Phase two consisted of a maize crop (*Zea mays* cv. Alfastar) planted with and without (control) a companion crop on 11th May 2017 in 12m replicates perpendicular to the direction of CC planting (Figure 5.1). Due to extremely dry soil conditions (22.4 %vol), shallow tillage (0-0.08m) was performed in order to allow the drill (Pöttinger Aerosem 3002 ADD drill with Fox D discs) to work correctly to establish the maize. The companion crop consisted of 1.0 kg ha^{-1} white clover (*Trifolium repends)* and 6kg Ha^{-1} tall fescue (*Festuca* arundinace cv Starlet). Following maize and companion crops, lettuce (*Lactuca sativa cv.* Black, Sumarnas, Oso-flaco) was transplanted into the field 21st – 25th June 2018.

Phase one of the trial was repeated at the Littleport trial site in 2018. Only the frost sensitive CC was selected for this trial as it has desirable characteristics from a farm management perspective (small biomass at the time of termination). The CC was zero till (Horsch Sprinter ST) established on the 24th August 2017 in replicate with control plots. There were 3 replicates of the control and CC treatment, each with a plot size of 24x80m. Glyphosate (4 l ha^{-1})

was applied across the trial on 21st April 2018 to terminate wheat volunteers in the control plots and remaining CC biomass. Maize (*Zea Mays* cv. P8200) was established on the 20th May 2018.

5.3.2 Soil Sampling

The treatments planned at Prickwillow created a mosaic of replicates across the field (Figure 5.1). There were a total of 9 replicates per treatment, of which 5 were randomly chosen for sampling at the end of phase 1 and phase 2. As the CC species within phase 1 were predominately cereal and brassica based the results from the frost sensitive and winter hardy CC treatments were pooled for analysis. Following phase 1, there was a control (n = 10) and a CC treatment (n=20). Following phase 2, there was the control (n= 5) and treatments: CC (n=10), companion crop (n=5) and cover & companion crop (n= 10).

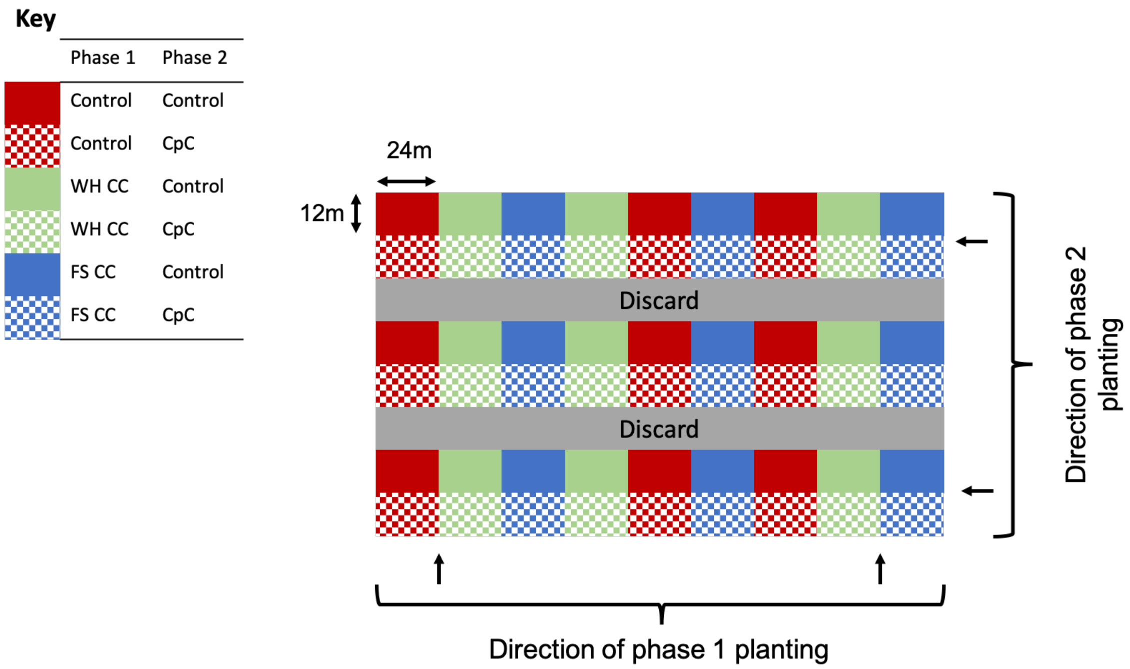

Figure 5.1: Schematic of trial plot layout at Prickwillow.

WH = winter hardy, FS = Frost sensitive and CpC = companion crop

At the conclusion of Littleport, phase 1, there were 3 replicates of the control and 3 replicates of the CC treatment.

The following methods were conducted at the conclusion of phase 1 and 2: visual evaluation of soil structure (VESS), shear strength, bulk density, penetration resistance and earthworm abundance.

General soil structure condition was assessed using VESS (Guimarães et al., 2011). As no compaction or soil texture layers were present the VESS was assessed over the entire block extracted (0.18x0.18x0.25 m) to the nearest half category- e.g. a score of 3.5 would denote a soil that was deemed to be halfway between firm (score 3) and compact (score 4) (Appendix E). Earthworms were hand sorted in 6 mins from the block of soil extracted for VESS. A bulk density ring of 0.053m dia and 0.029m height was inserted into the soil, extracted using a trowel with the soil trimmed to the volume of the metal ring before being placed into a sample bag. The soil sample was dried for 24hours at 105°C before bulk density was calculated with equation (5-1) where:

m_a - mass of soil sample and oven tin

m_b mass of oven tin

$$\frac{(m_a - m_b)}{\pi \; x \; 0.0265^2 \; x \; 0.029} \qquad (5\text{-}1)$$

Volumetric soil moisture content (Vol %) was determined at 0.1, 0.2 and 0.3m depths using a PR2 profile probe (Delta T, Burwell, UK). Soil moisture access tubes were installed 3 weeks prior to the first reading taken to allow the soil to settle around the access tube. During phase 2, 3 soil moisture access tubes were installed per treatment. For each probe at each depth, readings were taken every 120° (3 readings per depth) and were mean averaged to give one soil moisture reading per depth.

Soil penetration resistance was measured using a cone penetrologger (Eijkelamp) with a base area of 120mm^2 and speed 2ms^{-1}. Shear strength (Pilcon) measurements were made with a 19mm vane. Lettuce head mass was calculated by cutting and weighing 10 randomly selected lettuces per plot, the weight was then divided by 10 to give an average lettuce head mass (kg).

Soil characteristics (Table 5.1) were determined from a 3 sample composite taken per plot at 0-0.05m. The composite sample was mixed, sieved to <5.6mm and air dried prior to the analysis of: pH (MA235, Mettler Toledo, UK) with a 1:5 ratio of dried soil to water (BS ISO 10390:2005), soil organic matter (%) measured by loss on ignition (BS EN 13039:2011), total carbon (BS 7755-3.8:1995) and total nitrogen (BS EN 13654-2:2001) using the Elementar Vario III EL analyser.

Sampling at Prickwillow, phase 1 took place on 28th April and 2nd -3rd May 2017. An exceptionally dry spring in 2017 (Section 4.4.1), required the soil to be wetted up with water (140mm) to allow for VESS assessment and earthworms to be hand sorted. Sampling for both Prickwillow phase 2 and Littleport phase 1 took place 19th - 22nd March 2018. For each treatment, five of the nine plots at Prickwillow were sampled following phase 1 and phase 2. In each of the plots at Littleport and the plots selected per treatment at Prickwillow, one VESS assessment was conducted. Prior to the VESS sample extraction, bulk density was sampled at 0.05m and a further bulk density assessment was made at the bottom of the hole (0.25m depth) – both depths still in the peaty topsoil. Three shear strength assessments were made per plot at 0.05 and 0.15m depth and median averaged per depth. Five penetrologger measurements were taken per plot at 0.01m intervals to 0.3m, and median averaged per 0.01m depth.

5.3.3 Statistics

Differences were considered significant at $p<0.05$. Data was checked for normality (Shapiro Wilk's test) and the equality of variance (Levene's test) using the software RStudio, Version 3.4.1 (RStudio Team, 2016)

Following phase 1, at both Prickwillow and Littleport means of the soil quality indicators were tested using the T-Test. The one exception being earthworm population following phase 1, at Prickwillow, which were non-normally distributed and the Mann-Whitney test was used. Following phase 2, an unbalanced two-way ANOVA (Type II sum of squares (Langsrud, 2003)) was used to test for significance between treatment means and where appropriate the Tukey HSD *post hoc* tests were used. Standard error of the mean (SEM) is shown in the tables and figures.

5.4 Results

5.4.1 Visual Evaluation of Soil Structure

There was no difference in the VESS score between the control and the plots that had CCs between wheat and maize (phase 1) (Table 5.3). There was also no difference in VESS scores between the control and the companion crop (phase 2) sown with maize which overwintered following maize harvest.

Table 5.3: Mean VESS scores.

Site Year	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 1	3	3		
Littleport phase 1	2.5	2.5		
Prickwillow phase 2	2	2.5	2	2

5.4.2 Soil Shear Strength

There was no significant difference in soil shear strength ($p > 0.05$, t-test) between the CC treatment and control (phase 1) at both depths (0.05m and 0.15m). Compared with the CC only treatment the cover & companion crop treatment at Prickwillow (phase 2), significantly reduced shear strength at 0.15m depth ($p<0.05$); no significant difference was detected at 0.05m depth.

Table 5.4: Mean shear vane (kPa) readings recorded. Values in parentheses indicate SEM. Statistical significant difference between treatments is denoted by a different lower case letter across the row.

	0.05m			
Site Year	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 1	102.6 (6.9)	89.9 (4.6)		
Littleport phase 1	33.0 (1.5)	43.3 (4.8)		
Prickwillow phase 2	32.8 (4.0)	40.0 (2.9)	40.8 (2.3)	38.0 (2.2)
	0.15m			
Prickwillow phase 1	94.9 (6.5)	90.2 (7.2)		
Littleport phase 1	59.7 (6.1)	50.3 (4.6)		
Prickwillow phase 2	60.2 (6.5)^{ab}	67.1 (6.4)^{b}	50.2 (7.3)^{ab}	46.7 (4.0)^{a}

5.4.3 Bulk Density

At 0.05 and 0.25m depth (Table 5.5) there was no significant effect of the CC treatment when compared to the control (phase 1, both trial sites) on soil bulk density. Following phase 2 at Prickwillow, there was a companion crop main effect (Table 5.6) denoting significantly reduced soil bulk density at 0.05m in both treatments with companion crops (Figure 5.2). No significant difference was detected in bulk density at 0.25m depth following phase 2 (Table 5.5).

Table 5.5: Mean bulk density (Mg m^{-3}) readings. Values in parentheses denote SEM.

Site Year	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
		0.05m		
Prickwillow phase 1	0.85 (0.02)	0.86 (0.01)		
Littleport phase 1	0.86 (0.03)	0.87 (0.03)		
Prickwillow phase 2	0.87 (0.03)	0.90 (0.03)	0.83 (0.04)	0.84 (0.02)
		0.25m		
Prickwillow phase 1	0.86 (0.03)	0.84 (0.05)		
Littleport phase 1	0.78 (0.03)	0.85 (0.05)		
Prickwillow phase 2	0.90 (0.07)	0.88 (0.03)	0.91 (0.03)	0.90 (0.03)

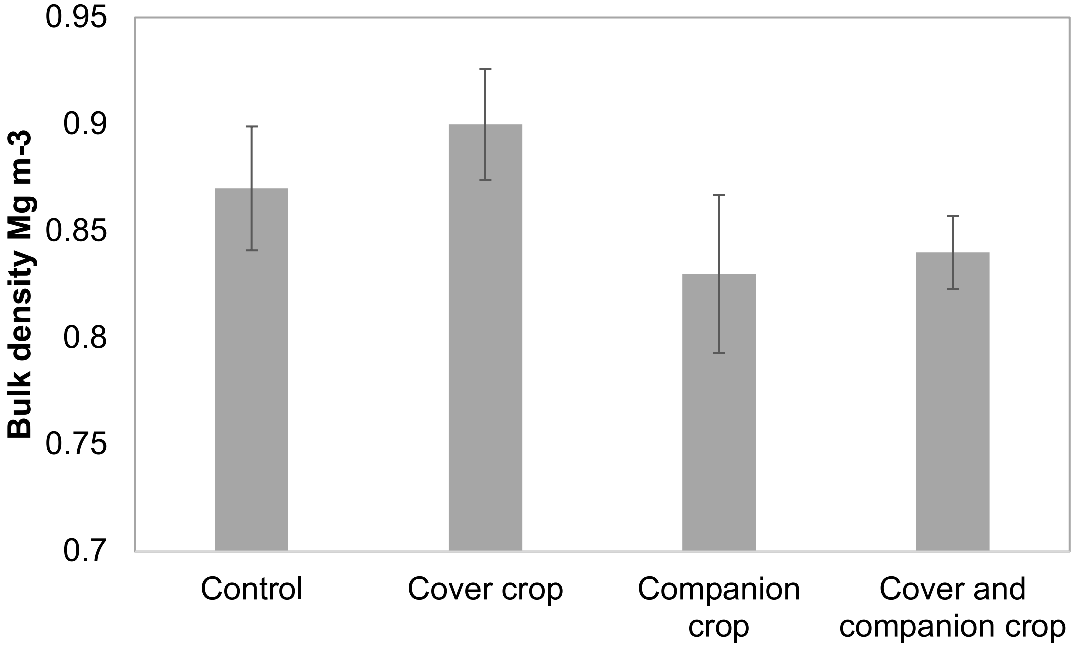

Figure 5.2: Bulk density readings at 0.05m depth following phase 2, Prickwillow. Error bars denote SEM.

Significant differences of the treatments could not be identified with theTukey HSD *post hoc* test in Figure 5.2 and Table 5.5 as level of significance is only slight at 0.045 (Table 5.6)

Table 5.6: Summary of the unbalanced two-way ANOVA of bulk density at 0.05m depth .

Source of Variation	d.f	F ratio	P value
Cover crop	1	0.5965	>0.05
Companion crop	1	4.6593	0.045
Cover crop * Companion crop	1	0.3463	>0.05
Residuals	26		

5.4.4 Soil Penetrative Resistance

In only one of two trial years at the depths of 0.08-0.12m (Figure 5.3, b) was there a significant difference ($p<0.05$, t-test) in soil penetrative resistance between the CC treatment and control in phase 1. At all other depths and in the previous trial year (Figure 5.3, a) there were no significant differences in soil penetrative strength when the CC treatment was compared to the control. The subsequent addition of a companion crop (phase 2), significantly reduced penetrative resistance at 0 -0.03m depth, though had no significant effect on soil strength when compared to the control at the majority of depths (Figure 5.4). Overall, there are isolated and limited significant effects of cover and/or companion crops on soil strength.

a) Prickwillow b) Littleport

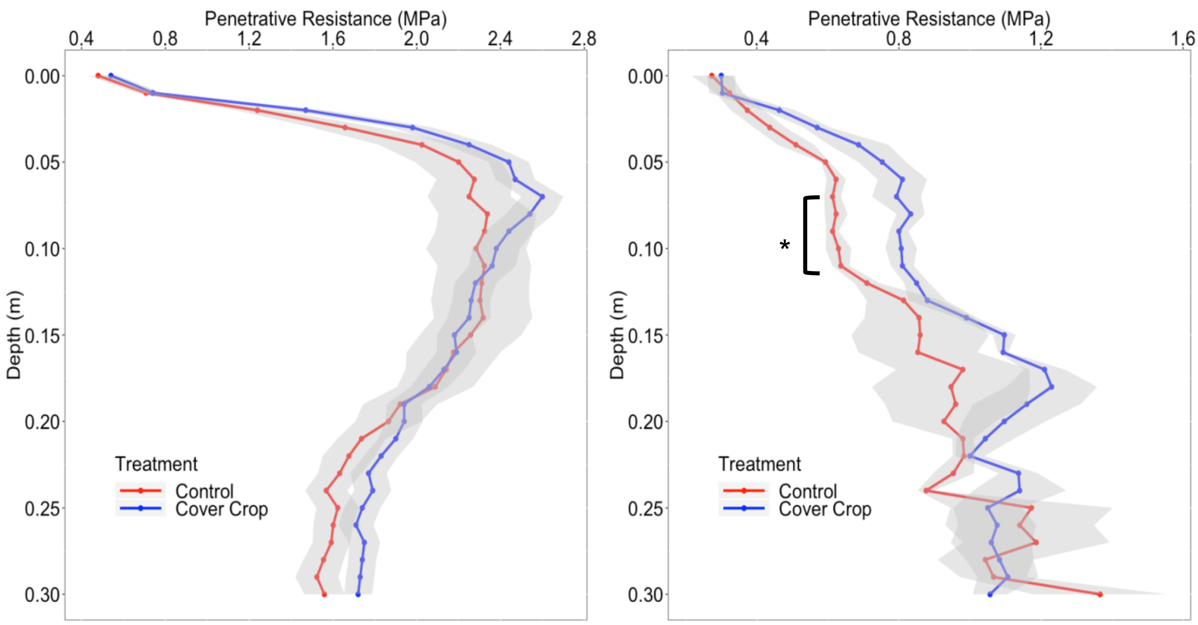

Figure 5.3: Soil strength following phase 1 at Prickwillow (a) and Littleport (b), respectively. Shaded area denotes standard error of the mean. See materials and methods for n per treatment at each site. Significant difference is denoted by * (t-test; p <0.05).

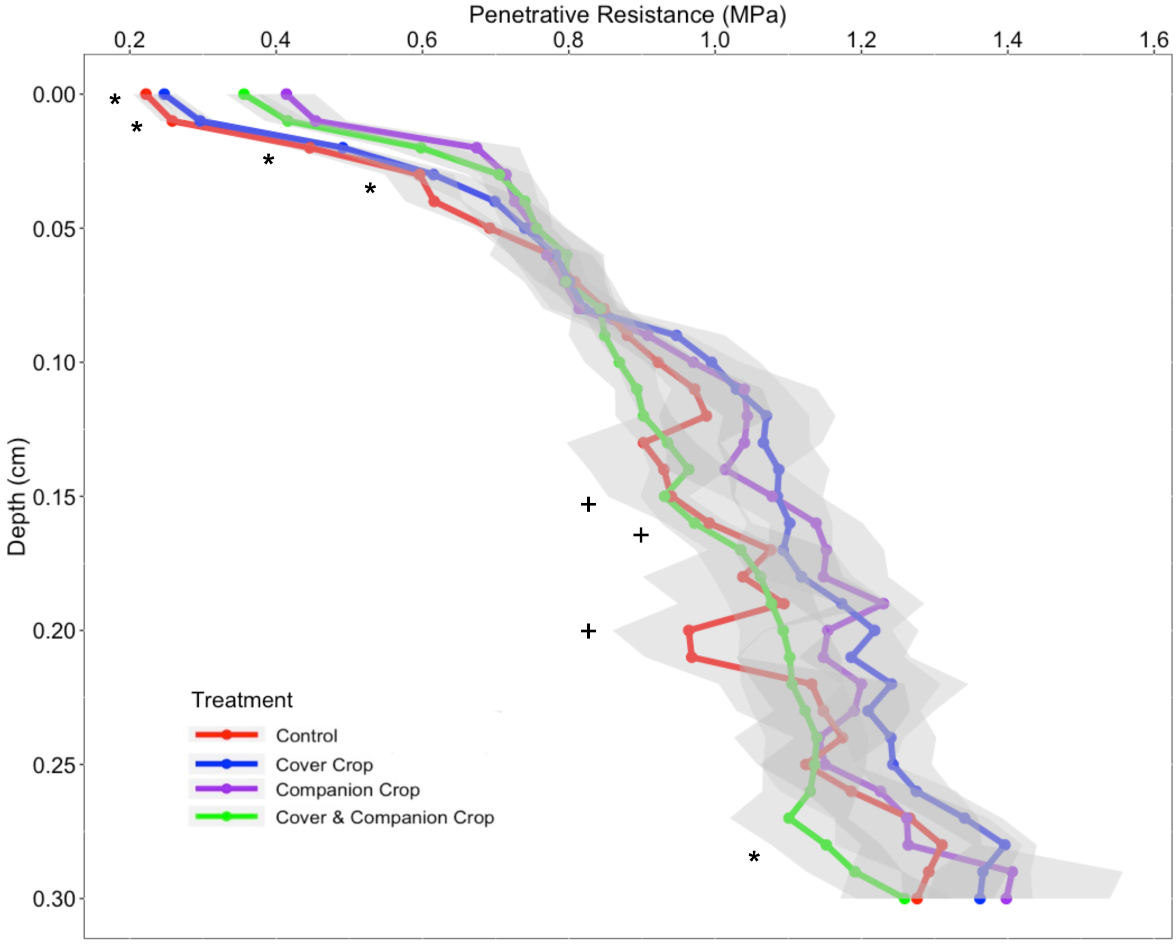

Figure 5.4: Soil strength following phase 2 at Prickwillow. Shaded area denotes the standard error of the mean. Significant difference (p <0.05) is denoted by the following symbols: + interaction between cover crop and companion crop; * main effect companion crop. See materials and methods for n per treatment for phase 2, Prickwillow.

5.4.5 Total Organic Carbon

No significant differences were detected in total organic carbon between the treatments at either phase 1 (T test p>0.05) or phase 2 (Two way ANOVA p >0.05).

Table 5.7: Mean TOC (%). Values in parentheses indicate SEM.

Trial site	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 1	14.1 (0.3)	13.4 (1.3)		
Littleport phase 1	13.8 (0.0)	13.9 (0.363)		
Prickwillow phase 2	13.5 (0.4)	12.8 (0.7)	13.7 (0.3)	14.0 (0.4)

5.4.6 Earthworm Abundance

There was no statistical difference in earthworm abundance following phase 1 at both Prickwillow ($U = 135$, $p > 0.05$) and Littleport (t test, $p > 0.05$) (Table 5.8). Following phase 2, there was a statistical interaction between the main effects of a CC and companion crop on earthworm abundance, thus *post hoc* analysis was not carried out. Analysis of the simple effects (Section 6.4.1), indicates that the presence of the preceding CC (phase 1) influenced the effect of the companion crop on earthworm abundance. Greater earthworm abundance was associated with the treatments that were sown with a companion crop.

Table 5.8: Mean earthworm abundance. Values in parentheses indicate SEM.

Trial site	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 1	354	216		
Littleport phase 1	144 (27)	144 (37)		
Prickwillow phase 2	333 (60)	398 (60)	895 (91)	617 (59)

5.4.7 Soil Moisture Overview

There were no significant differences (t-test; $p > 0.05$) in soil moisture measured between the control and CC during phase 1 Prickwillow and Littleport (Section 4.4.1). However, there was up to a 20% difference in volumetric soil moisture between phase 1, Prickwillow (2017) and phase 1, Littleport (2018) (Table 5.9). At the time of sampling at phase 2, Prickwillow, there were no significant differences ($p > 0.05$) between the treatments at any depth (Table 5.10).

Table 5.9: Average volumetric soil moisture (Vol %) at the time of penetrologger sampling taken during phase 1 at Prickwilllow and Littleport on 28th April 2017 and 20th March 2018, respectively. Values in parentheses denote SEM. An * denotes statistical significance (T-test; p <0.05).

Depth (m)	Prickwillow phase 1 (2017)	Littleport phase 1 (2018)
0.1 *	22.9 (2.3)	42.5 (5.5)
0.2 *	29.4 (13.4)	45.8 (8.3)
0.3 *	39.4 (8.5)	50.4 (4.4)

Table 5.10: Soil moisture (Vol %) recorded 28th March 2018 following phase 2, Prickwillow. Values in parentheses denote SEM.

Depth (m)	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
0.1	43.8 (3.5)	42.9 (1.2)	41.4 (3.6)	43.5 (5.1)
0.2	47.5 (8.1)	44.7 (26.4)	45.1 (7.3)	43.2 (6.1)
0.3	50.0 (4.2)	48.1 (0.7)	51.0 (6.7)	47.6 (3.3)

5.4.8 Lettuce Yield

There was no significant difference ($p > 0.05$) in lettuce head weight following the different treatments. Lettuce yield results should be interpreted with caution as they do not account for the differences in varieties or planting dates.

Table 5.11: Mean lettuce head mass (kg). Parenthesis indicate SEM

Trial site	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 2	0.47 (0.0)	0.51 (0.0)	0.48 (0.0)	0.45 (0.0)

5.5 Discussion

5.5.1 Visual Evaluation of Soil Structure

Generally, there was only a limited effect of cover and/or companion crops on the quantitative soil physical quality indicators: bulk density, shear strength and penetration resistance. In addition, VESS assessments indicated that there was no effect of CCs on the structure and porosity of the topsoil when assessed visually (Table 5.3).

VESS is a quick and easy to follow method that is able to capture important information regarding macro-porosity and aggregation (Guimarães et al., 2017). VESS has been shown to be well correlated to other soil physical indicators (bulk density, soil porosity, penetration resistance) and can distinguish between tillage treatments or different land uses well (Askari et al., 2013; Cherubin et al., 2017; Giarola et al., 2010). The methodology has been used by other researchers (Abdollahi & Munkholm, 2014; Stobart et al., 2015) and has recently been demonstrated to farmers in the UK as part of the GREAT Soils project (AHDB, 2018). Stobart *et* al.,(2015) reported that CCs improved soil structure (lower Sq score) when compared to a stubble - although it is not clear if volunteers were a feature of the stubble control. The data presented from this trial compared the use of CCs to a control on which wheat volunteer grew. It was unlikely that the semi-quantitative VESS method (scored at 0.5 intervals) was precise enough to describe any differences in soil structure due to rooting differences between the tap and fibrous rooted CC treatment and the fibrous roots of the wheat volunteers present in the control (Table 5.3). Rotational differences, (similar to a CC treatment compared to a control with wheat volunteers) are more difficult to consistently detect, despite recording VESS to a greater precision of half of a category (e.g. 3.5 halfway between firm and compact). Scoring VESS to greater precision (a third of a category, (Nathan Morris, *personal communication*)) may help to distinguish the subtle changes made by CCs (Stobart et al., 2015). However, reporting to greater precision than this (e.g. one or two decimal places) may not reflect the physical meaning of the VESS categories (Askari et al., 2013).

Recent research has recommended that 5 VESS measurements are taken per field/ treatment; and is regarded as the optimal number of measurements required to manage the trade-off between time required and accuracy (Leopizzi et al., 2018). With only three true replicates at the Littleport trial, it was not possible to conduct the optimal number of VESS assessments per treatment. Thus, a limitation of the trial at Littleport, phase 1 was the lack of replicates (3) for the control and treatment. In all instances, the VESS assessment was ≤ sq3 which is the threshold at which, to avoid negative effects on crop growth ,soil remediation by tillage should be considered (Ball et al., 2007). Additionally, research has shown that VESS is not well correlated with earthworm abundance (or ants) and may explain why a greater difference in VESS scores was not recorded following phase 2 at Prickwillow, despite a considerably greater earthworm abundance in the treatments with a companion crop (Table 5.8)(Franco et al., 2017).

5.5.2 Quantitative Physical Soil Quality Indicators

Soil shear strength measurements were used to assess soil cohesion and is more strongly correlated to the draught force required by tillage implements than penetrologger measurements (Arvidsson & Keller, 2011). At 0.05m depth there was no significant difference between the treatments and control nor was there a trend between the treatments (Table 5.4). At 0.15m depth the cover & companion crop treatment of phase 2 significantly reduced shear strength, and the companion crop treatment lead to a reduced shear strength compared to the control and CC treatment. The reduced shear strength in the treatments with a companion crop is unlikely related to soil moisture given the non-significant differences in soil moisture at 0.1 and 0.2m depth (Table 5.10). Treatments with companion crops were characterised by greater earthworm abundance (Table 5.8), which have been positively correlated with reduced shear strength (Clements et al., 1991). During tillage, shear strength is the dominant force generated, thus a reduction in soil shear strength can reduce the draught requirement and thus, the fuel required for the subsequent tillage operations needed for lettuce transplants (Arvidsson & Keller, 2011; Stafford & Tanner, 1983).

There were no significant differences in bulk density following the growth of CCs when compared to the control after phase 1 (Table 5.5). This was not unexpected given the short time period (8 months) for which the CCs were established and that CCs have previously been shown to only reduce soil bulk density by approximately 1% (Alvarez et al., 2017). Following phase 2 at Prickwillow, a significant main effect of companion crops was detected at 0.05m depth (Table 5.6), but differences between the treatments could not be identified using Tukey HSD *post hoc* tests. The reduced soil bulk density at 0.05m could, again, be related to the increased earthworm abundance (Table 5.8) in the treatments with companion crops when compared to no companion crops. Additionally, a tall fescue companion crop allocates 37% of its root length in the 0-0.1m soil depth (Perkons et al., 2014) and this may have increased macro-aggregation compared to the bare soil control of phase 2 (Linsler et al., 2016).

Overall, soil penetration resistance was low, due to the high organic matter content (25% +), low clay content and lack of stones. Soil penetration resistance measurements conducted following phase 1 at Littleport and phase 2 at Prickwillow were below 2 MPa, the value at which root growth may become restricted (Hamza & Anderson, 2005). Soil penetrative resistance measured following phase 1 at Prickwillow was greater than 2Mpa between 0.02 and 0.2m depth (Figure 5.3, a). Greater soil moisture during 2018 reduced soil penetration resistance following phase 1 at Littleport and phase 2 at Prickwillow when compared to measurements taken in 2017 following phase 1 at Prickwillow (Table 5.9, Table 5.10) (Bengough et al., 2011).

Following phase 1 at Littleport, there was a significantly greater ($p<0.05$) soil penetration resistance at 0.08-0.12m depth following the CC treatment when compared to the control. Data from phase 2, after the addition of companion crops to the trial showed that significant differences between the treatments were limited, with only a significant main effect of the companion crop at 0-

0.03m depth (Figure 5.4). Chen and Weil (2011) report that no significant differences were detected in soil penetrative resistance or bulk density measurements following CCs after 1 season. Rather, they inferred compaction alleviation due to CCs by assessment of maize crop root growth using the core break method to count roots at certain depths. Other authors have noted that it may take up to four years of CC use for soil penetrative resistance to decrease (Mupambwa & Wakindiki, 2012) and for other soil properties to change (Jokela et al., 2009) following CCs.

The following reasons have been cited for the lack of difference between CC and control treatments for soil penetrative resistance 1) a large cone tip several orders of magnitude larger than the root tip, does not adequately represent root growth, 2) a series of biopores in a small volume of soil would need to intersect the penetrologger tip in order to result in a reduced penetrative resistance (Chen & Weil, 2011). Given the low penetrative resistances recorded in this trial, it may be assumed that the CC roots, particularly the main tap root, would grow vertically in the soil profile. As the action of penetrologger and root growth act in the same direction it was unlikely that the cone tip would encounter these larger biopores that are left behind from the roots following CC senescence. Rather, the cone tip encounters the soil aggregates that have been pushed laterally by root growth, which was significantly greater in the CC treatment (Appendix F) and may partially explain the trend for increased soil penetrative resistance measured in the CC plots (Figure 5.3) in both years (Chen & Weil, 2011). Soil penetration resistance is sensitive to soil moisture. However, this is unlikely to explain the increase in soil penetration resistance measured in the CC treatment during phase 1 because there were no significant soil moisture differences between the control and treatments at 0.1, 0.2 or 0.3m depth (Table 5.10, Section 4.4.1) (Whalley et al., 2006).

There were no differences to TOC following the use of CCs or companion crops, which is consistent with other findings (Beehler et al., 2017; Sánchez de Cima et al., 2015). The inherently high OC content of the soils in this field trial (2.62×10^5 kg C ha^{-1}) require that sampling protocol and analysis equipment is sufficient to detect a 0.15% increase in OC given that CCs, on average in mineral soils, increase SOC at a small rate each year (320-490 kg C ha^{-1} yr^{-1}), (Poeplau & Don, 2015; Ruis & Blanco-Canqui, 2017). Furthermore, the addition of the CCs and companion crops increased the soil microbial biomass carbon (Section 6.4.2) thus carbon was consumed by the soil microbial population and lost through respiration to the atmosphere (Gougoulias et al., 2014). Overall there is no net gain of SOC over the short duration of this trial.

As soil degradation can be slow and take several years to materialise it can be expected that the improvement to soil quality will be slow to accumulate following changes to soil management practices (Acuna & Villamil, 2014; Kibblewhite et al., 2008). Another reason for the lack of significant differences between the treatments in the majority of the soil physical quality indicators is the natural tendency of the organic soil to restructure itself. The high organic matter content of the soil swells with the absorption of water from rainfall and shrinks due to the loss of water through drainage and evapotranspiration (Dessureault-Rompré et al., 2018). These drying and wetting cycles occur over the duration of the CC period and may have a greater effect than one season of CCs and the addition of companion crops to the rotation.

Finally, no difference in lettuce head weight was detected following phase 2, Prickwillow. This is unsurprising given that uniform, intensive, tillage to 0.15m depth took place – shallow compared to traditional practices of inversion tillage to 0.3m. The greater soil disturbance from tillage would have homogenised the soil at 0-0.15m depths and thus removed the few physical significant differences that existed between the treatments. Furthermore, the variables introduced by the multiple lettuce planting dates and varieties could not be accounted for at the time of lettuce head weight sampling.

5.6 Conclusion

When compared to the wheat volunteers that grew in the control, the addition of CCs into the rotation between the wheat and maize crop increased the penetration resistance of the soil in both years, but only significantly at 0.08-0.12m in one of these two years. The subsequent establishment of the companion crop with the maize that overwintered after maize harvest significantly reduced the bulk density and shear strength at 0.05 and 0.15m depth, respectively. The companion crop also reduced soil penetration resistance at 0-0.03m depth. These significant changes may be related to the greater earthworm population present in the companion crop treatments as well as the roots of the tall fescue. Overall, the effect of CCs and companion crops on soil structure and compaction in the short term (<20months) was confined to a few specific depths. Assessment of the general condition of the topsoil (0-0.2m) using the VESS method did not distinguish any considerable differences between the treatments. The short trial period may not have been sufficient for soil physical changes to develop but equally the selected measurements may not have been sensitive enough to distinguish between the small changes that could occur in a high organic matter soil when comparing the effects of the CCs to a control plot that grew with wheat volunteers. Alternative in-field physical soil quality indicators (e.g. infiltration, aggregate stability) and advances in technology would aid the investigation of soil structural changes due to CCs in the short term.

6 THE EFFECT OF COVER CROPS ON EARTHWORM, MICROBIAL AND FUNGAL COMMUNITIES

6.1 Abstract

Cover crops (CC) provide a continuity of roots and organic matter in the rotation when there may otherwise be bare soil. By providing a habitat and food source this can influence the soil biological community, which can alter soil function affecting the following crop's growth and ecosystem services. Understanding how the soil biological community responds to CCs grown in a wheat – maize - lettuce rotation can help ensure CCs are selected and managed to deliver benefits to all crops in the rotation and enhance ecosystem services, through improved soil management. Two field trials in Ely, Cambridgeshire (2016 to 2018) measured the effect of the presence of a multi-species CC mixture and/or a companion crop on earthworm abundance, microbial carbon and fungal biomass and microbial community diversity. In the 8 months of CC presence between wheat and maize there was no significant difference in earthworm abundance or microbial carbon and fungal biomass. However, after a companion crop was established with maize to become an overwinter CC, earthworm population and microbial biomass carbon significantly increased as well as the phospholipid fatty acid biomarkers associated with fungi.

6.2 Introduction

Cover crops (CC), sown between periods of cash crop production, are unharvested crops that are sown for the benefit of soil function to aid crop production and contribute to other ecosystem services. CCs can enhance water quality by reducing nitrate leaching and soil erosion and can also sequester carbon for climate regulation (Cooper et al., 2017; De Baets et al., 2011; Marcillo & Miguez, 2017; Poeplau & Don, 2015). CCs, through the provision of resources (carbon and nutrients) support the earthworm and soil microbial communities at a time in the rotation that may otherwise be bare soil or arable weeds (Finney et al., 2017a; Bertrand et al., 2015). CC biomass provides carbon following senescence of the plant tissues but also during plant growth through rhizodeposition (Austin et al., 2017). Microbial communities and earthworm populations are important soil quality indicators as they have a fundamental role in litter breakdown (Coleman et al., 2004). Litter decomposition, mediated by soil biota, affects nutrient cycling, soil organic matter accumulation and soil structure (Müller et al., 2017; Zhou et al., 2017).

Soil biota improve the architecture of the soil. Burrowing and feeding activity of earthworms enhance soil structure through the formation of stable soil aggregates and continuous macropores (Shipitalo & Korucu, 2016). This aids water infiltration, reduces run-off and provides bio-pores for root growth (Kautz et al., 2014; Korucu et al., 2018). Additionally, earthworm casts are enriched with plant nutrients that aid plant growth (Stroud et al., 2016). Plant nutrient availability is further aided by arbuscular mycorrhizae fungi (AMF) which form symbiotic relationships with 80% of plant roots, the exception being species of the brassicaceae family (Wang & Qiu, 2006). CCs enhance the AMF abundance by ≈50%, and the fungal hyphae that extend into the rhizosphere are an important mechanism for many plants to acquire phosphorus, nitrogen and water, especially in nutrient poor soils or small soil pores (Drinkwater et al., 2017; Hallama et al., 2018). The mining activity of the fungal hyphae are able to explore a greater volume of the soil compared to root hairs to access plant available phosphorus. As a non-renewable and often limiting nutrient in agriculture, phosphate supply may also be increased through the phosphatase activity and microbial P sources that are enhanced through the use of CCs (Hallama et al., 2018). Additionally, fungal hyphae networks and the secretion of glomalin improve aggregate stability and macro-aggregation that, enmesh organic matter protecting this source of carbon from the decomposition process of other soil microorganisms (Bedini et al., 2009; Six et al., 2006).

Decomposition of plant residue is driven by the soil biota and is essential for the cycling of macro nutrients and trace elements with specialized microbial communities favoured depending on substrate and energy available (Fontaine et al., 2003). The soil microbial population also regulates soil organic matter decomposition and/or sequestration. Microbial activation due to the labile carbon released from plant roots is linked with the decomposition of the soil organic matter (rhizosphere priming effect) (Zhu et al., 2014). Poeplau & Don (2015) propose this as one of two reasons why a decrease in SOC stocks was measured in 9% of the plots studied in the meta-analysis of the effect of CCs on carbon sequestration; even if the microbial population, following death forms part of the non-living SOM (Miltner et al., 2012).

CCs are used in a variety of agronomic contexts and CC species specific effects have been observed in earthworm populations and microbial communities (Finney et al., 2017a; Martínez-García et al., 2018; Roarty et al., 2017). Brassicas are unable to form AMF associations which reduced the colonisation of AMF on the roots of the following crop (Njeru et al., 2014; Wang & Qiu, 2006). Brassicas, due to the glucosinolate content of their residues may act as a biofumigant and reduce soil borne diseases (Morra & Kirkegaard, 2002). However, under field conditions the effect of biofumigation is variable: 27% reduction of powdery scab pathogen inoculum in potato crops (Larkin & Griffin, 2007), no effect on S. *minor* sclerotia in lettuce crops (Bensen et al., 2009) and reduction of R. *solani* pathogenic activity in carrots is only measured in the short term following mustard incorporation. Furthermore brassica CCs (mustard and forage rape) result in a significantly reduced earthworm population compared to a legume CC (pea) (Roarty et al., 2017).

Similar to physical structural changes due to CCs (Çerçioğlu et al., 2006; Jokela et al., 2009), changes to the soil biological community may take several years to accumulate and are likely to be hindered by any tillage operations (Schmidt & Curry, 2001; Somenahally et al., 2018). CCs established in intensive rotations with substantial soil disturbance, may not lead to marked changes in the soil biology (Norris & Congreves, 2018).

This research was undertaken to critically evaluate the effect of CCs on soil quality through an assessment of earthworm abundance, microbial and fungal biomass and microbial community diversity following the inclusion of CCs between wheat and maize followed by a companion crop established with maize.

6.3 Materials and Methods

The trial followed a rotation of wheat – maize – lettuce in Ely, Cambridgeshire. CCs were planted between wheat and maize (phase 1) and a companion crop was established with the maize and remained as an over winter CC following maize harvest (phase 2). Phase 1 CCs were established between wheat and maize at two field sites: Prickwillow, 2016–2017 and Littleport 2017-2018. Phase 2 followed phase 1 only at the Prickwillow trial site in 2017-2018. Both sites had the same soil type (Drainic Sapric Histosol) although the organic horizon in some places was *circa* 0.4m depth indicative of a Mollic Gleysol. Soil characteristics of the field trial sites are given in Table 6.1.

Table 6.1: Soil characteristics of field sites

Soil characteristic	Prickwillow	Littleport
pH	7.7	7.4
Total Carbon %	14.0	15.1
Total Nitrogen %	1.0	1.1
Soil Organic matter %	25.4	26.8

The Prickwillow, phase 1, trial was established in a 6 ha field on 26th August 2016 after wheat (cv. Skyfall) was harvested on the 14th August 2016 and the uniform application of digestate liquor at 40m^3 ha^{-1} on the same day. In triplicate two multi-species CC mixtures (Table 6.2) were zero till (Horsch Sprinter ST) established alongside non-planted control plots that were 24m wide. Wheat volunteers subsequently grew on the control plots. Glyphosate was applied (4.0 l ha^{-1}) across the trial site to terminate wheat volunteers and any remaining CC plants on the 7th April 2017.

Table 6.2: Cover crop species planted at Prickwillow, August 2016.

Frost sensitive mixture (25 kg ha^{-1}) £42 ha^{-1}	Winter hardy mixture (30 kg ha^{-1}) £36 ha^{-1}
60% Cadence black oats	60% Protector forage rye
Avena stigosa cv. Cadence	*Secale cereal* cv. Protector
35% Final oil radish	30% Evergreen oil radish
Raphanus sativus cv. Final	*Raphanus sativus* cv. Final
5% Braco White mustard	10% Berseem clover
Sinapis alba cv. Braco	*Trifolium alexandrium*

Phase 2, at Prickwillow only, consisted of forage maize (cv. Alfastar) crop planted with and without (control) a companion crop. The phase 2 treatment (with companion crop) and control were established perpendicular to the direction of establishment of the treatments of phase 1. The treatment and control of phase 2 consisted of three replicates and were 12m wide. Below average spring rainfall (9mm of rain between 24th March – 11th May 2017) led to extremely dry soil conditions (22.4 % vol). In order to allow the drill (Pöttinger Aersoem 3002 ADD drill in combination with Fox D discs) to correctly and place the maize seed accurately shallow tillage (to 0.08m depth) was performed prior to maize and companion crop establishment. The companion crop consisted of 1.0 kg ha^{-1} white clover (*Trifolium repends)* and 6 kg ha^{-1} tall fescue (*Festuca* arundinace cv. Starlet). In May 2018, the maize stovers and companion crop were flailed (to reduce maize stover size) and had an application of glyphosate (4 l ha^{-1}) prior to tillage for lettuce (cv. Black, Sumarnas, Oso-flaco) that was transplanted between 21st – 25th June 2018.

Phase 1 of the trial was repeated at the Littleport trial site in 2017. Only the frost sensitive CC was selected for this trial as it had desirable characteristics from a farm management perspective (reduced biomass at termination). This CC was zero till (Horsch Sprinter ST) established on the 24th August 2017, following wheat harvested on 12th August 2017. Glyphosate (4.0 l ha^{-1}) was applied across the trial on 21st April 2018 to terminate wheat volunteers in the control plots and the remaining CCs. Forage maize (cv. P8200) was established on the 20th May 2018. There were 3 replicates of the control and CC treatment in plots 24m x 80m.

In both years the trial plots received the farm standard agronomic interventions associated with maize nutrition and fungicide applications. At the Littleport trial herbicide was applied during maize growth. This was not compatible with the Prickwillow field trial as companion crops were established as part of some of the treatments.

6.3.1 Soil Sampling

Soil sampling of phase 1 and 2, Prickwillow followed the same protocol and methods outlined in section 5.3.2.

After phase 1, earthworms were sampled on 3rd May 2017 at Prickwillow and the 21st March 2018 at Littleport. Following phase 2, earthworms were sampled on 22nd March 2018 at Prickwillow. Earthworms were hand sorted in the field from a spit of soil that measured 0.18 x 0.18 x 0.25m and counted in 6 minutes. At the conclusion of the trials at Littlport (phase 1) and Prickwillow (phase 2) soil samples at 0-0.05m depth were collected on 4th April and 5th May 2018, respectively, for the laboratory analysis of microbial carbon and fungal biomass, and phospholipid fatty acid (PLFA) analysis. Three sub samples (circa 200-300g) were taken per plot and mixed to form a composite. The fresh soil samples were sieved to 4mm and stored at 4°C for microbial biomass extraction and freeze-dried for ergosterol extraction (fungal biomass) and PLFA analysis. For site characterisation, soil samples were collected at the start of the trials at Prickwillow and Littleport on 2nd September 2016 and 4th September 2017, respectively. Again, three soil sub samples (0-0.05m depth) per plot were collected, combined to form a composite and air dried for the analysis of pH, soil organic matter and total carbon and nitrogen.

6.3.2 Laboratory Methods

Microbial biomass carbon (MBC) was determined using the fumigation extraction method (BS 7755: 4.4.2:1997). For each sample retrieved from the field, duplicates of fresh sieved soil were weighed out to the equivalent of 12.5g of oven dry soil. One duplicate was fumigated using chloroform for 24hours (Jenkinson & Powlson, 1976). Following this, 50ml of 0.5mol/l potassium sulphate was added to both sub-samples to extract the organic carbon and filtered through a Whatman No. 42 filter. Microbial biomass was calculated by the difference between the fumigated and non-fumigated duplicate samples following analysis on a SFA-2000 segmented flow analyser (Burkard Scientific, Herts, UK) and adjusted by the proportionality coefficient (k_{EC} = 0.45)(Joergensen, 1996).

Ergosterol content of the soil was determined from a simplified, rapid ultrasonification method (Ruzicka et al., 1995). Duplicates of 4-6g were weighed out per sample. One duplicate was spiked with 1ml of ergosterol (100µg) in n-hexane:2-propanol (98:2 v/v). Following 15mins at room temperature, 10ml of methanol:ethanol (4:1 v/v) was added before leaving at 4°C for 2 hours. To both duplicates n-hexane:2-propanol (98:2 v/v) was added at 20 and 19ml for the unspiked and spiked duplicate, respectively and cooled on an ice bath before sonicating at 150W for 200s. 2ml of the top layer was removed and centrifuged at 10,000 rev min^{-1} and the supernatant injected into the high-performance liquid chromatography machine (SCI Tek instruments, Olney, UK).

PLFA profiles were extracted according to the method described by Frostegaard et al.,(1991) as based on the method described by Bligh and Dyer (1959) and White et al., (1979). Phospholipids were extracted from 10g of freeze dried soil using Bligh and Dyer (1959) solvent at a ratio of 0.8:1:2 (v\v\v) for citrate buffer, chloroform and methanol, respectively. Solid phase extraction was used to extract the phospholipids. Mild alkaline methanolysis was used to the form fatty acid methyl esters (FAMEs) from the phospholipid fraction (Dowling et al., 1986). FAMEs were analysed using gas chromatography (Aglilent Technologies, Santa Clara, CA, USA). The mol % of fatty acids were used to analyse the following indicator groups of organisms: Bacteria (15:0, 15:0i, 15:0ai, 16:0i, 17:0ai, 17:0i, 17:0 (12Me), cyc17:0 isomer); Fungi (16:1ω5, 18:2ω6,9); AMF (16:1ω5) and non-categorised (14:0, 16:1ω11t, 16:1ω7c, 17:0br, 17:0c, 17:1ω8c, 17:1ω8t, 17:1ω7, 17:1ω7, Me17:0 isomer, Me17:0 isomer 2, 18:0, 18:1ω7t, 18:1ω13, 18:0(10ME), 19:0c, 19:1ω6, 20:0, 20:4, 20:5ω3) (Frostegård & Baath, 1996; Olsson, 1999).

For the determination of trial site characteristics soil was air dried prior to the analysis of: pH with a 1:5 ratio of dried soil to water (BS ISO 10390:2005), soil organic matter (%) measured by loss on ignition (BS EN 13039:2011), and total carbon (BS 7755-3.8:1995) and nitrogen (BS EN 13654-2:2001) after dry combustion using the Elementar Vario *III* EL analyser.

6.3.3 Statistical Analysis

Differences were considered significant at $p<0.05$. Data was checked for normality (Shapiro Wilk's test) and homoscedasticity (Levene's test) using the software RStudio, Version 3.4.1 (RStudio Team, 2016)

Following phase 1, at both Prickwillow and Littleport means of the soil indicators were tested using the T-Test. The exception was earthworm population following phase 1, Prickwillow, as the data was non-normally distributed so the Mann-Whitney test was used with a sample size of n = 10 and 20 for the control and CC treatment respectively. At Littleport, there were 3 replicates of both the control and CC treatment.

Following phase 2, an unbalanced two-way ANOVA (Type II sum of squares (Langsrud, 2003)) was used to test for significance between treatment means and where appropriate the Tukey HSD *post hoc* test was used. This was due to the unbalanced number of replicates: control (n= 5) and treatments: CC (n=10), companion crop (n=5) and cover & companion crop (n= 10). Standard error of the mean (SEM) is shown in the tables and figures. Principle component analysis was conducted using the FactoMineR package in R Studio (Le et al., 2008; R Core Team, 2017).

6.4 Results

6.4.1 Earthworm Abundance

Following phase 1, there was no statistical differences between earthworm abundance at either Prickwillow ($U = 138$, $p > 0.05$) or Littleport, $t(4) = 0$, $p = 1$ (Table 6.3).

Table 6.3: Average earthworm abundance per m^2 following phase 1. Values in parentheses indicate standard error of the mean (SEM).

Trial site	Control (No cover or companion crop)	CC (No Companion crop)
Prickwillow	354	216
Littleport	144 (27)	144 (37)

Following phase 2, a significantly greater earthworm abundance was measured in the treatments with companion crops as opposed to the treatments without companion crops (Figure 6.1). The unbalanced two-way ANOVA (Table 6.4) indicated statistical interaction between the presence or not of a CC and companion crop and therefore the simple effects were investigated rather than a post *hoc* test. Analysis of the simple effects (Table 6.5) indicates that the presence of the preceding CC (phase 1) influenced the effect of the companion crop on earthworm abundance.

Figure 6.1: Mean earthworm abundance per m^2 following phase 2 at Prickwillow. Error bars indicate SEM. No *post-hoc* test due to statistical interaction.

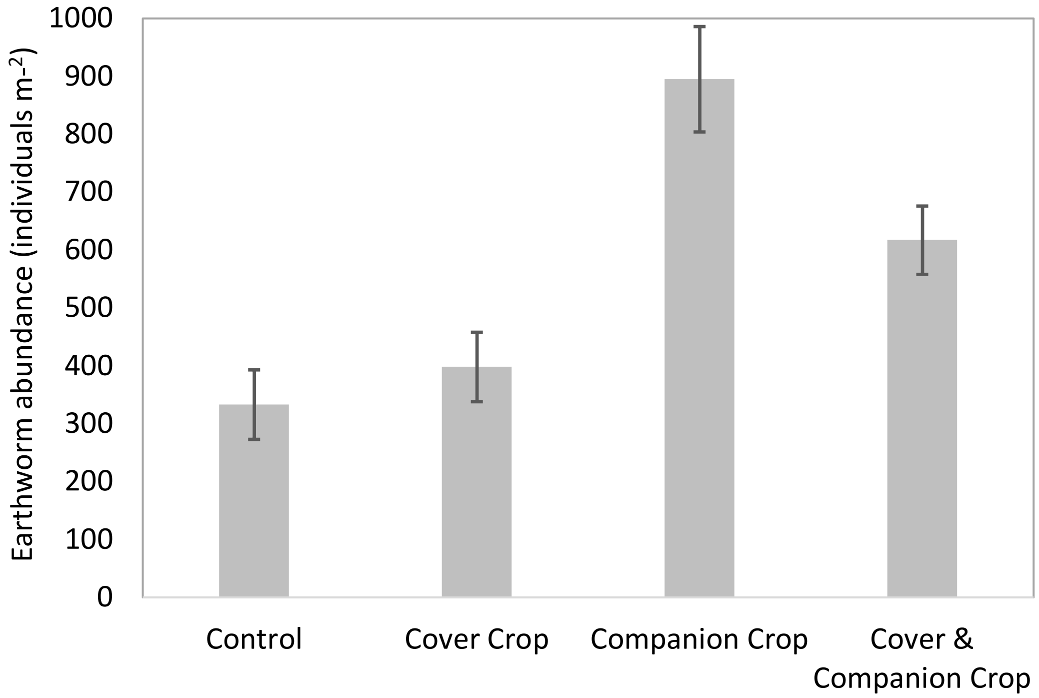

Table 6.4: Summary of the two-way ANOVA of earthworm abundance per m^2.

Source of Variation	d.f	F ratio	P value
Cover crop	1	2.2339	>0.05
Companion Crop	1	24.6626	<0.001
Cover crop * Companion crop	1	5.7815	<0.05
Residuals	26		

Table 6.5: Simple effects analysis of the two-way ANOVA of earthworm abundance per m^2

Controlled effect	Source of variation	d.f	F ratio	P value
No cover crop	Companion crop	1	26.37	<0.001
	Residuals	8		
Cover crop	Companion crop	1	6.7645	<0.05
	Residuals	18		
No companion crop	Cover crop	1	0.4501	>0.05
	Residuals	13		
Companion crop	Cover crop	1	7.0354	<0.05
	Residuals	13		

6.4.2 Microbial Biomass Carbon (MBC)

Following phase 1 at Littleport, no significant difference in MBC between the control (M = 610, SEM = 38) and CCs (M = 705, SEM = 30) was measured, with conditions; t (4) = -1.95, p = 0.12. At the conclusion of phase 2, at Prickillow, the combination of cover & companion crop significantly increased MBC compared to the control (Figure 6.2); both main effects, CC and companion crop, significantly increased MBC (Table 6.6)

Figure 6.2: Mean microbial biomass carbon (ug g $^{-1}$ soil). Error bars indicate SEM. Treatments with the same letters are not significantly different following unbalance two-way ANOVA and *post-hoc* Tukey HSD tests.

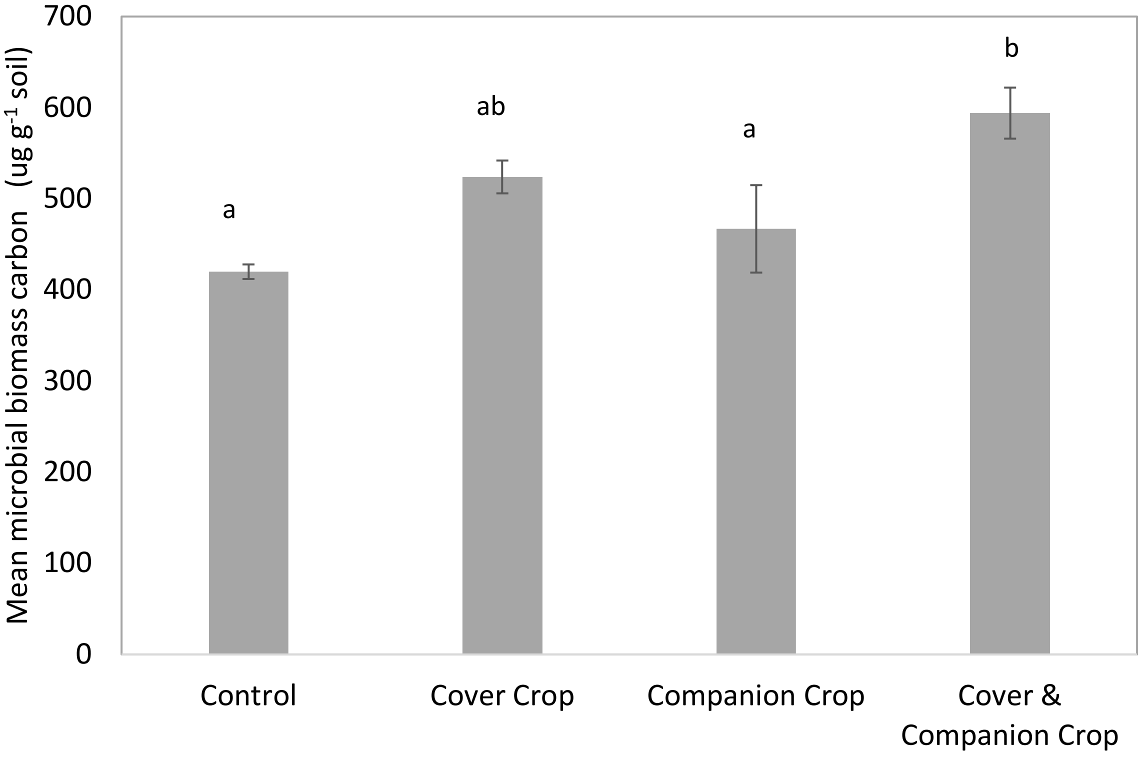

Table 6.6: Summary of two way ANOVA for MBC.

Source of Variation	d.f	F ratio	P value
Cover crop	1	15.8851	<0.001
Companion crop	1	5.1737	< 0.05
Cover crop * Companion crop	1	0.1494	>0.05
Residuals	26		

6.4.3 Fungal biomass

Following CCs between wheat and maize at Littleport (phase 1), there was no significant difference in fungal biomass between the control (M = 2.11, SEM = 0.36) and CC treatment (M = 2.84, SEM = 0.52) with conditions; $t(4) = -1.14$, $p = 0.32$.

At Prickwillow, following phase 2, no significant differences were recorded between the treatments for fungal biomass (Table 6.7).

Table 6.7: Mean fungal biomass determined by extraction from the soil mg g^{-1}. Values in parentheses indicate SEM.

Trial site	Control (No CC or companion crop)	CC (No Companion crop)	Companion Crop (No CC)	CC & Companion Crop
Prickwillow phase 2	2.31 (0.16)	2.21 (0.12)	2.92 (0.52)	2.37 (0.08)

6.4.4 Phospholipid Fatty Acid Analysis

The PLFA analysis following phase 2, at Prickwillow, showed that the companion crop and the CC & companion crop treatments were composed of a different microbial community, as evidenced by their shift to the left of the control treatment (Figure 6.3). This may be the result of the strong negative contribution of fungi biomarker 18:2ω6,9 in PC1 (Figure 6.4) (Frostegård & Baath, 1996). All the treatments with a CC and/or companion crop increased the microbial diversity when compared to the control, which has a narrow diversity indicated by the size of the ellipses in Figure 6.3.

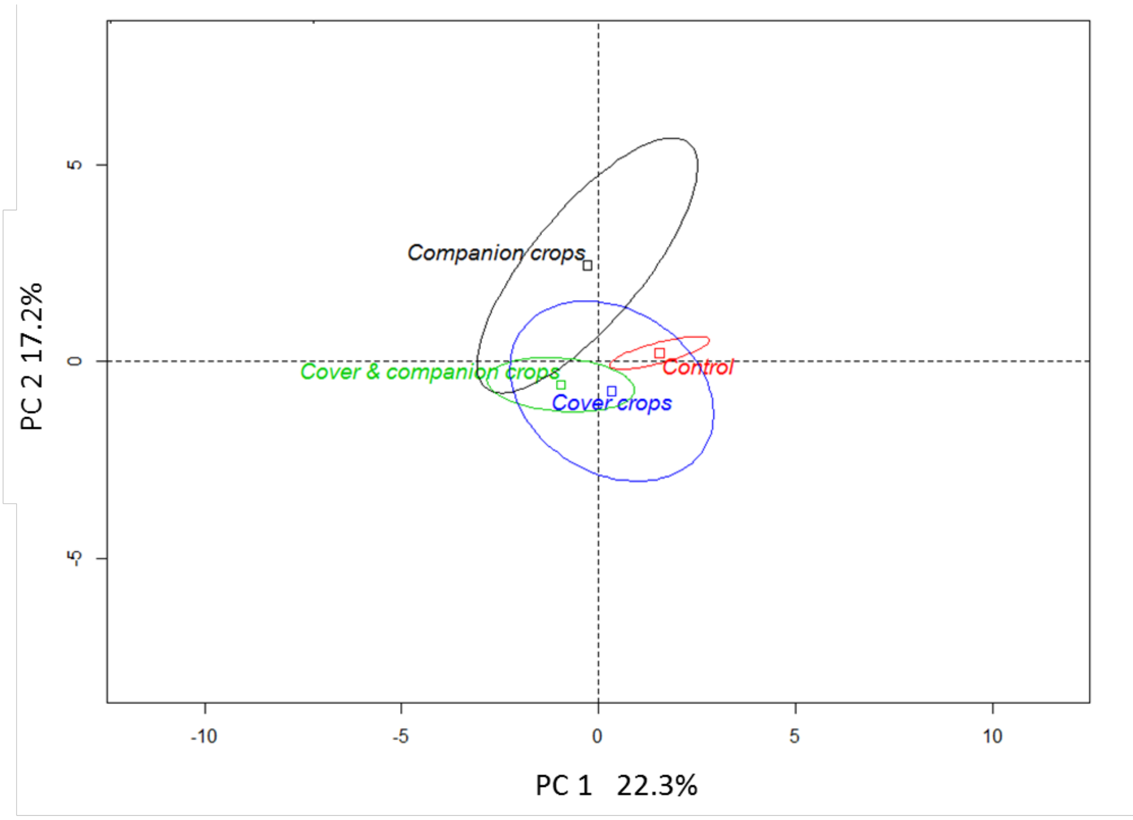

Figure 6.3: Principle component analysis of the PLFA data from phase 2, Prickwillow. Ellipses = 95% confidence.

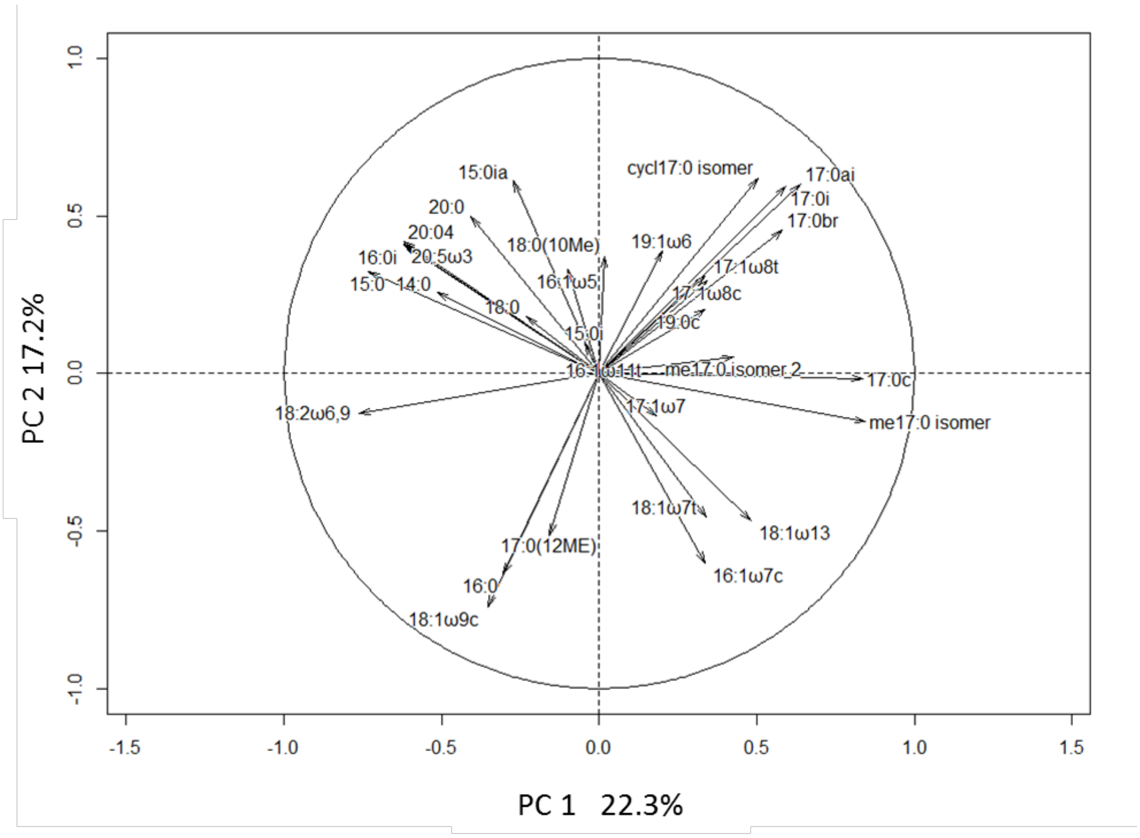

Figure 6.4: Individual loading values of the FAME biomarkers that contribute to the first two principle components of the PLFA analysis from phase 2, Prickwillow.

After phase 1, at Littleport, the FAME biomarkers representing bacteria, fungi and AMF showed that there was no significant difference (t test; $p > 0.05$) in mean relative mol% of the fatty acid profiles associated with these groups between the control and CC treatment (Table 6.8). This is in agreement with the microbial and ergosterol biomass results.

Table 6.8: Mean relative mol % of selected FAME biomarkers to represent the following groups: bacteria, fungi and AMF. n = 3. Values in parentheses denote SEM.

FAME functional group	Control	CC
Bacteria	16.31 (0.039)	16.11 (0.554)
Fungi	7.07 (0.030)	7.61 (0.154)
AMF	4.70 (0.015)	4.66 (0.026)

Following phase 2, at Prickwillow, FAME biomarkers indicating the relative mol% of fungi and AMF were significantly greater following the inclusion of a companion crop ($p<0.05$) (Table 6.9, Table 6.10). The companion crop only treatment contained significantly greater fungi and AMF biomarkers when compared to the CC only treatment. Bacterial biomarkers indicated that there was no significant difference between the treatments following phase 2 at Prickwillow.

Table 6.9: Mean relative mol % of selected FAME biomarkers to represent bacteria, fungi and AMF groups. Within each FAME functional group, significant differences (p <0.05) between treatments are indicated by a differing lower case letter. Values in parentheses denote SEM.

FAME functional group	Control (No cover or companion crop)	CC (No Companion crop)	Companion Crop (No CC)	CC & Companion Crop
Bacteria	18.99 (0.035)	18.71 (0.078)	18.99 (0.058)	18.64 (0.047)
Fungi	6.06^{a} (0.11)	6.21^{ab} (0.05)	6.84^{c} (0.071)	6.7^{bc} (0.015)
AMF	5.03^{ab} (0.078)	4.86^{a} (0.021)	5.33^{b} (0.055)	5.17^{ab} (0.016)

Table 6.10: Two-way ANOVA summaries for the FAME biomarkers representing bacteria, fungi and AMF

		Bacteria		Fungi		AMF	
Source of Variation	d.f	F ratio	P value	F ratio	P value	F ratio	P value
Cover Crop	1	3.854	>0.05	0.000	>0.05	1.966	>0.05
Companion Crop	1	0.095	>0.05	14.659	<0.001	8.118	<0.01
Cover Crop * Companion Crop	1	0.057	>0.05	0.831	>0.05	0.000	>0.05
Residuals	26						

6.5 Discussion

6.5.1 Earthworm Abundance

At two separate trials, Prickwillow and Littleport, CCs between wheat and maize (phase 1) did not significantly affect the earthworm population when compared to the control (wheat volunteers). These findings are in agreement with Stroud *et al.,*(2017) who reported that oilseed radish, as a single species CC did not increase the number of L. *terrestris* midden counts within 4 months of establishing the cover crop or following a longer term trial of 8 years. Korucu *et* al., (2018) also reported that a rye CC did not significantly increase L. *terrestris* populations, however there was a significant increase in overall earthworm population following the rye CC due to a significant increase in Aporrectodea *spp.* Analysis to species level was not part of the current study due to a high number of juveniles present. Roarty *et al.,* (2017) reported that CCs, (brassicas, cereals, legume and phacelia) did not significantly increase earthworm abundance compared to a bare fallow or natural regeneration following 3 years of CC and spring barley rotation. As the control naturally regenerated with wheat volunteers, it was able to provide a food source for earthworms so it is not surprising that there is no significant difference in the earthworm population between the Control and the CC treatment of phase 1. Thus, the wheat volunteers have the same effect on earthworm population as the CC between wheat and maize but without the expense of seed and establishment costs (labour and fuel). Alternatively, if wheat volunteers are considered as a weed then the greater wheat volunteer biomass in the control (9.1 t ha^{-1}) as compared to the CC treatment (2.5 t ha^{-1}) (data not shown for brevity) demonstrates the weed suppression capabilities of the CC (Brust et al., 2014).

There was an increased earthworm population with the addition of a companion crop, following phase 2, Prickwillow. The greater time period of continuous plant presence and lack of deep or inversion tillage provided favourable conditions for earthworms. Intensive tillage, known to reduce earthworm populations (Gerard & Hay, 1979), was last carried out prior to the planting of wheat at Prickwillow in 2015, with only a shallow tillage operation (to 0.08m) prior to maize establishment in 2017. Due to very dry conditions, tillage was performed to create a seed bed for maize, but the dry top soil may have forced the earthworms to greater depths for soil moisture thus avoiding the tillage performed to 0.08m depth. Continuous plant cover and without soil disturbance can lead to increased earthworm populations after two years (Han et al., 2015a; Schmidt & Curry, 2001).

Greater earthworm population in the companion crop only treatment as opposed to the cover & companion crop treatment (Figure 6.1) may be explained by companion crop establishment (plant count as opposed to plant biomass). Companion crop establishment of the tall fescue was 3x greater following the control of phase 1 when compared to the CC treatment (Appendix G). The reason for the difference in companion crop growth is likely due to the residue type from the preceding CC. When brassica residues are mixed into the soil the seedling emergence of the following crop can be reduced (Haramoto & Gallandt, 2004). This is the most plausible explanation rather than poor seedling emergence due to residue interference with seed placement that can reduce seed-soil contact. Following phase 1, there was greater aboveground biomass in the control plots from the wheat volunteers when compared to the aboveground biomass of the CC treatments. Therefore, if poor establishment was due to poor seed-soil contact as a result of residue in the plots, reduced companion crop establishment would be associated with the control. However, this was not observed; sparse companion crop establishment was a feature of the plots that followed the CC treatments of phase 1.

The low earthworm population recorded in the control and CC-only treatment of phase 2, at Prickwillow was expected given that there was no vegetation growing overwinter (Oct 2017 – May 2018) and therefore, there was no food source or habitat for an earthworm population. This demonstrates the importance of maintaining vegetation throughout the rotation to enhance earthworm abundance.

6.5.2 Microbial Biomass and Community Composition

Following phase 2, at Prickwillow there was a strong significant legacy effect of CCs from phase 1 on MBC, despite CCs being present in plots at least 13 months prior to the sampling date (Figure 6.2). Increased MBC following CCs is reported in other research (Mitchell et al., 2017; de Oliveira et al., 2016) and in the analysis of ecosystem services provided by CCs (Daryanto et al., 2018). Greater MBC was associated with the treatments with a greater biomass productivity and plant diversity, which provided greater organic carbon to sustain the microbial population (Geisseler et al., 2016).

Despite the contribution of aboveground biomass from the frost sensitive CCs during phase 1, at Littleport, there was no immediate significant effect of the CC treatment on MBC when compared to the control. Several months may be required for soil MBC to change following the use of CCs (Jackson et al., 2004). The immediate increase of MBC after CCs was measured following their incorporation, which aerates the soil and provides a sudden and considerable mass of CC residue instantaneously, when compared to CCs that have gradually senesced due to the frost (Wyland et al., 1996).

No significant differences in fungal biomass were observed between the treatments following Littleport phase 1 or Prickwillow phase 2 (Table 6.7). However, similar trends and some significant differences were observed when FAME biomarkers are used to represent the fungal (18:2ω6:9 and 16:1ω5c) and specifically AMF (16:1ω5c) functional groups. Following phase 1, at Littleport fungal biomass and fungal biomarkers increased, but were not significantly different following CCs as compared to the control (Table 6.8). The high percentage of brassicas, included in the CC mix, do not form AMF associations and would not have encouraged AMF presence (Njeru et al., 2014). Following phase 2, there were significant differences between the treatments and the control when assessed using the FAME biomarkers for fungal groups (Table 6.9). The companion crop in phase 2 was predominately composed of tall fescue (Appendix G), which can form AMF relationships (Covacevich & Echeverría, 2009) and resulted in significantly greater mol % of biomarkers associated with fungi and AMF in the companion crop only treatment. The companion crop only treatment followed the control of phase 1 (wheat volunteers), and thus with plant species in both phases that host AMF, led to an increased fungal biomass and AMF associated biomarkers at 0-0.05m soil depth (Minoshima et al., 2007). Without a suitable host (brassica CCs of phase 1 or the bare soil control of phase 2) AMF hyphae reduce over time (Kabir, 2005). Thus, there is a decreased mol % of FAME biomarkers associated AMF depending on the presence or not and type of vegetation present in the treatments: companion crop > cover & companion crop > control > cover crop. The promotion of AMF following the companion crop, may, in addition to nutrient acquisition benefits, improve resistance and tolerance to disease (Delavaux et al., 2017), drought (Quiroga et al., 2017) and salinity (Selvakumar et al., 2018). The benefits of AMF may become increasingly important in areas of intensive horticultural production (such as the Fens, U.K.) where low summer rainfall requires horticultural crops to be irrigated regularly increasing soil salinity (Machado & Serralheiro, 2017).

The discrepancy in results between fungal biomass and FAME biomarkers used to identify microbial functional groups is unclear. Whilst the use of FAME biomarkers to denote microbial functional groups is used by the research community (Finney et al., 2017a; He et al., 2013), there are concerns over the practice (Frostegård et al., 2011), so results should be interpreted with caution.

The first two principle components from phase 2, at Prickwillow only explain approximately 40% of the microbial variation in the population (Figure 6.3) but they were sufficient to show that the CC & companion crop and companion crop only treatment were different from the control. The different plant species used in the CC and/or companion crop treatments increased the diversity of the soil microbial population, as evidenced by the larger confidence ellipses (Figure 6.3). It is suggested that a greater diversity of CCs at multiple spatial scales can increase the diversity of soil microbial community leading to a decrease in soil disease and pathogens (Maron et al., 2011; Vukicevich et al., 2016). It has been shown that specific CCs enhance certain microbial communities for example oats and cereal rye promote AMF (Finney et al., 2017a). AMF are pathogen antagonists which compete for root space and can prime a plant immune response (Jung et al., 2012).Disease suppressive bacteria can produce antimicrobial compounds as well as compete for resources (Latz et al., 2012). Thus, the greater plant diversity associated with CC and companion crop treatments can promote soil microbial diversity and potentially reduce soil borne disease and pathogens. The shift of the microbial community of the treatments containing a companion crop to the left of the control could be driven by the markers associated with fungal groups, 16:1ω5 and 18:2ω6,9 (Figure 6.4). These fungal biomarkers had been shown to be significantly greater in those treatments with companion crops (Table 6.9). More distinct differences between the treatments and control may not arise as soil type can be the most dominant factor in soil microbial community composition (Bossio et al., 1998).

6.6 Conclusion

This study demonstrates the need for continuous vegetation throughout the winter period to promote greater earthworm population - even in the presence of shallow tillage. Furthermore, soil MBC was significantly increased following CCs from the first phase, however this is a legacy effect given that the measurement took place 13 months following CC termination. There was no significant effect of CCs or companion crops on fungal biomass. However, the use of FAME biomarkers for fungal groups showed that there was an increased abundance (relative mol %) of fungi and AMF following companion crop treatments which may can benefit soil structure, plant growth via nutrient acquisition and tolerance to drought, salinity and disease. Companion crops resulted in a greater earthworm abundance when compared no companion crops and bare soil. However, when the two treatments containing companion crops were compared, the selection of a high percentage of brassicas in the preceding CC, reduced the establishment of the following companion crop and subsequently the earthworm abundance too. Therefore, consideration needs to be given to CC species selection so that subsequent plant growth isn't negatively affected, reducing the potential to improve earthworm population.

7 DISCUSSION

The aim of the research was to understand the effect of CCs on soil quality indicators in a cereal and salad rotation. This required an understanding of the use and management of CCs in the UK, so that field trials could be managed successfully and in line with best practice. New knowledge was gained regarding the effect of CCs on selected physical, chemical and biological soil quality indicators in organic soils used for intense horticultural production. Additional insights into effective CC management were also gained from the farm trials as part of the research. Furthermore, the majority of soil quality indicators were assessed using methods that were accessible to farmers, so knowledge regarding their suitability as on-farm methods to assess the effect of CCs in the short term is also evaluated. Finally, the use and management of CCs is discussed in an agricultural policy context.

7.1 Effects of Cover Crops on Soil Quality Indicators

Two CC periods were considered in this field trial between i) wheat and maize and ii) maize and lettuce. The rotation allowed for the effect of CCs to be assessed after only one CC period but also to evaluate if there is added benefit of having a second consecutive CC period that was initially established as a companion crop. The effect of CCs on soil quality indicators in this study are summarised in Table 7.1.

Table 7.1: Overview of cover crop periods and their effect on soil quality indicators.

Key:

No effect	Limited effect	Increase	Decrease

Rotation period	Cover Crop	Companion Crop
Control	Wheat volunteers	Bare soil
Accumulated time	8 months	21 months
Soil Quality Indicators		
Soil structure	×	×
Soil available nitrogen *	✓	✓
Soil moisture	×	✓
Total organic carbon	×	×
Earthworm abundance	×	✓
Microbial biomass carbon	×	✓
Fungal biomass	×	×
Microbial community structure	×	✓
Crop yield	×	×

*the split indicates the general differences measured over Autumn, Winter and Spring.

The field trials aimed to assess the ability of CCs to improve soil structure and alleviate soil compaction, which is considered a major threat to soils in the U.K. (DEFRA, 2009a). Improvement to general soil structure following CCs has been reported in the UK (Stobart et al., 2015), but the alleviation of soil compaction by CCs when measured using a penetrometer may take several years (Chen & Weil, 2011; Mupambwa & Wakindiki, 2012). This study supports these findings, as there was no significant alleviation of soil compaction or improvement of topsoil structure following one CC period when compared to the control. The decision to select brassica CC species for the first CC period was for its ability to alleviate soil compaction with a tap root but there was little evidence that this occurred (Figure 5.3). Therefore, the hypothesis that CCs improve soil structure and reduce soil compaction after one CC period is rejected and the null hypothesis is accepted. However, the hypothesis that a second CC period (the companion crop) will ameliorate soil structure and reduce soil compaction is accepted. This is evidenced by the significantly reduced penetrative resistance (Figure 5.4), soil strength (Table 5.4) and bulk density (Table 5.5) at discreet depths following the companion crop compared to the control.

CCs can reduce soil moisture (Krstić et al., 2018; Nielsen et al., 2016) or retain soil moisture (White & Weil, 2010) depending on CC management and species. Soil moisture at 0.1, 0.2 or 0.3m depths did not differ following a FS CC when compared to a control that subsequently grew with wheat volunteers (Figure 4.2). Rather the soil moisture is affected to a greater extent by the rainfall pattern of the season as evidenced by the two contrasting seasons of the trial. Winter rainfall is sufficient to replenish the soil moisture used by a significantly larger CC biomass (Basche et al., 2016). Therefore, using CCs over the winter period in the U.K. are unlikely to dry out soils by early spring. However, the companion crop that grew over winter and into late spring significantly reduced soil moisture from mid-April onwards when compared to a bare soil control (Appendix I). In mid-April, the greater temperatures and day length than the previous months stimulate companion crop growth, (Appendix G) and so evapotranspiration is increased. Rainfall was not able to replenish the soil moisture lost due to this increased transpiration. Therefore, CCs that are maintained after mid spring can reduce soil moisture which could reduce the yield of the following crop - especially in drier seasons (Nielsen et al., 2015b). The hypothesis that a single CC period will reduce soil moisture is dependent on i) weather and ii) time of the year at which the CC is terminated. Therefore, the hypothesis that the soil moisture is reduced ahead of a spring crop is rejected with respect to a frost sensitive CC between wheat and maize. However, the hypothesis is accepted for conditions after using a winter hardy companion crop (that was not terminated until late May), where it was shown that soil moisture was deleted in the Spring.

Soil N immobilisation following CCs was a concern for some farmers (Storr et al., 2019) and soil N dynamics due to CCs is also highlighted as a knowledge gap in an AHDB funded review (White et al., 2016). Soil available N dynamics are affected by CC biomass, and so with a frost sensitive CC, the biomass of which is changing in response to weather, it is necessary to understand the implications of this to soil available N (Silgram & Harrison, 1998). Therefore, assessment of soil available N was made at 3 week intervals – a higher resolution of sampling than previous studies in the UK (Baggs et al., 2000; Cooper et al., 2017). The data collected in this study supported the hypothesis that a frost sensitive CC initially reduced soil available N during CC growth until frost senescence in mid-Winter. Following senescence soil available N began to increase and was significantly increased by late Winter (Figure 4.4). This would provide a greater soil N benefit to earlier sown spring crops such as wheat or barley but, in a wet spring may pose a risk to N leaching if late sown spring crops such as maize or potatoes are to be planted (Dean & Weil, 2009). However, wheat volunteers in the control are as effective as the CC at reducing soil available N in the autumn but maintain a reduced soil available N content throughout Winter and Spring compared to the CC treatment. Measured at only two time points (early May) prior to their termination, the companion crop significantly reduced soil available N (Appendix H). The companion crops were winter hardy and actively grew from mid-March onwards (Appendix G), thus reducing soil available N.

Earthworms and the soil microbial community are vital for the decomposition of organic matter, soil structure and soil fertility (Shipitalo & Korucu, 2016). Earthworm abundance can be CC species specific and it can take several years for the population to build up (Roarty et al., 2017; Stroud et al., 2017). Increased soil microbial diversity can improve resilience to soil pathogens (Vukicevich et al., 2016) with CCs also having species specific effects on the microbial community (Finney et al., 2017a). This study showed that an initial CC period when compared to a control of wheat volunteers did not have any significant effect on earthworm abundance (Table 6.3), MBC, or FAME biomarkers associated with bacteria and fungi (Table 6.8). However, a subsequent second CC period that was sown as a companion crop significantly increased earthworm abundance (Figure 6.1), MBC and FAME biomarkers associated with fungi (Table 6.9). Furthermore the diversity and abundance of the microbial community (Figure 6.3) was increased due to the diversity of plant species of the CC and companion crop compared to the control. Thus, the importance of a continuous and diverse plant cover for increased earthworm and microbial abundance is highlighted in this study. The hypothesis that a single CC period can increase the i) abundance of earthworms and ii) abundance and diversity of the microbial community is rejected as no significant difference following the first CC compared to the control was observed. However, the hypothesis is accepted for conditions following a second CC period (established as the companion crop) where differences in earthworm abundance and microbial community composition were observed between the companion crop treatments and the control.

CCs, a source of organic matter have been shown to add 320-490 kg C ha^{-1} yr^{-1} to the TOC pool of mineral soils which can improve soil fertility and also mitigate against climate change (Poeplau & Don, 2015; Ruis & Blanco-Canqui, 2017). However, this is a small amount of C to measure annually against the high TOC (2.62×10^5 kg C ha^{-1}) present in the soils used in the trials of this study. Thus, no significant differences in TOC were measured following the addition of two CC periods into the rotation (Table 5.7) and the null hypothesis is accepted. Furthermore, despite the addition of C from CCs (<490 kg C ha^{-1} yr^{-1}) it would never be able to replace the amount of carbon that is lost through mineralisation from agricultural activities, which is estimated to be 25 28t CO_2-eq ha^{-1} yr^{-1} or approximately 6.8 – 7.6 t C ha^{-1} yr^{-1} (Evans et al., 2016).

Yield differences following CCs are variable. Previous studies have reported increased (Chen & Weil, 2011; Kramberger et al., 2009), decreased (Nielsen et al., 2016; Tonitto et al., 2006) and no difference (Gabriel & Quemada, 2011; Dozier et al., 2017) to yield following CCs. The survey conducted as part of this study highlighted that 45% of respondents who used CCs were unsure of their effect on cash crop yield whilst 12% were able to quantify their effect on cash crop yield. In this study, the null hypothesis is accepted as there were no significant effects of CCs on either maize yield (Table 4.2) after one CC period or lettuce yield (Table 5.11) after two CC periods. For CCs used in these rotations there does not seem to be a yield penalty.

The measurement of the specific indicators (e.g. N availability, TOC) allows for assessment of soil function provided that they are specific, measurable and sensitive to change (Karlen et al., 1997). As soils can be slow to respond to land use or management changes, some indicators are more suited than others to measure changes in soil quality and associated effect on soil function. It is generally accepted that biological soil quality indicators are the most sensitive to change than other indicators (Bünemann et al., 2018). The soil quality indicators used in this research that were the most sensitive to change were the soil biological indicators (earthworm abundance, microbial community diversity, FAME biomarkers) soil available N. Physical soil quality indicators showed some minimal changes and no change was detected in TOC. Once soil function has been assessed using soil quality indicators (Karlen et al., 1997), the effect on ecosystem services can then be evaluated given that an individual soil function contributes to an ecosystem service (Bouma, 2014; Greiner et al., 2017). As the research investigated the effect of CCs on soil quality indicators the effect on ecosystem services can inferred, via the effect of CCs on soil function.

The research indicates that CCs in the short term do not provide a measurable benefit to climate regulation (through increased C sequestration) or crop production (via crop yield improvements). Importantly, no detrimental effect to climate regulation or crop production was measured from the use of CCs in the short term. Effects on climate regulation and crop production will also be affected by many other externalities such as drainage (loss of CO_2) and weather (water availability to crop). The limited significant effects on physical soil quality indicators, were unlikely to improve soil structure (soil function) and produce a crop yield response. Using shallow tillage (to 0.08m) in the research reduced disturbance of the soil and the cover and companion crop also provided a habitat for soil organisms. This resulted in increased abundance and diversity of earthworms and micro-organisms, respectively, indicating an improved habitat provision service. Furthermore, frost sensitive CCs, aided nutrient cycling (regulating service) through the reduction of soil available N in the autumn, which likely improved water quality by reducing the potential for soil N leaching. Then upon senescence increased soil available N from mid-Winter onwards for uptake by the following crop.

Overall, the use of CCs did not improve crop yield, however there were benefits to the following soil functions: nutrient cycling, habitat provision and soil structure (limited).

7.2 SQI Selection and Efficacy

The interest in measuring and monitoring soil quality is growing and is the focus of a current AHDB project with a particular focus on soil biological indicators (AHDB, 2017). Provided there is a control, the majority of soil quality indicators used in this project would be suitable for use on farm. However, their effectiveness in measuring differences in the short term is worth further discussion. It is evident from the research that time is required for the effect of CCs to accumulate and that the sensitivity of the on farm soil quality indicators are critical to the determination of the size of the effect measured - if any.

Differences to soil biological indicators were only evident after two CC periods; therefore, the farming community should be made aware of the time required to measure changes to soil biological indicators following changes to soil management practices. Earthworm counts are widely used and easy to conduct and may be further enhanced by the identification of species/ classification to ecological groups (Open Air Laboratories (OPAL), 2016). This was attempted in the presented research, but the large number of juveniles meant that it was not possible to accurately identify a sufficient population of the earthworms to species level. The success of the 60 minute earthworm initiative shows the popularity and willingness of the farmers to measure soil quality indicators on farm, provided the methods are simple to conduct and results are easy to understand (Stroud & Watts, 2018). MBC and fungal biomass are soil quality indicators that can be easily sampled on farm and transported to commercial laboratories for assessment, and produce easily understandable results. PLFA analysis allows for the microbial community to be assessed and microbial functional groups can also be distinguished; although, this is controversial as some FAME biomarkers belong to more than one microbial functional group (Frostegård et al., 2011). PLFA, whilst expensive compared to the MBC and fungal biomass, provides a more in-depth analysis of the soil microbial community. In the future, soil DNA meta barcoding analysis may provide further in depth analysis of the soil microbial community, though the research is in its infancy and the cost at present is prohibitive (FERA, 2018). A greater understanding of the diversity and microbial groups in present in the soil would allow farmers to select CC species or farm management practices that enhance particular soil microbial communities for the benefit of the following crop. For instance legume CCs enhance AMF when compared to other CC species and is particularly beneficial to maize crops rather than other cereal crops (Hallama et al., 2018). Additionally, soil pests and disease may be promoted or inhibited following the use of different CC species; farmers would then wish to select CCs based on how they affect soil-borne pathogens. Differences to soil physical indicators, as measured by the methods of this study reveal that significant differences following the use of CCs are limited in the short term. The physical soil quality indicators selected were likely not sensitive enough to differentiate between the phase 1 control growing with wheat volunteers and the CC treatment with a different root architecture. But also changes to soil structure resulting from CCs may take several years before differences are measured (Jokela et al., 2009; Mupambwa & Wakindiki, 2012).

The use of VESS, penetration resistance, bulk density and shear vane assessments are widely used to identify soil compaction and poor soil condition. But in the short term (< 20months) it was difficult to differentiate between CCs and a control. VESS assessment is well correlated to other physical soil quality indicators (but not earthworm abundance) and is useful to identify general soil condition and where tillage may be required to remediate compaction (Guimarães et al., 2013; Franco et al., 2017). However, this research and that of Askari *et al*.,(2013) suggests that VESS is not sensitive enough to always detect rotational differences (CCs compared to wheat volunteers/bare soil) in the short term. Bulk density and penetrative resistance are commonly used to identify soil compaction, and the differences arising from tillage. However, only limited significant differences, at discreet depths, were detected with a digital penetrologger and bulk density ring. Assessment of soil cohesion with a shear vane was able to distinguish between treatments with a companion crop present. Overall, soil physical quality indicators struggled to detect meaningful differences due to the subtle effect of a cover and/or companion crop.

Soil water infiltration and aggregate stability (slake test) may be suitable methods to infer differences about soil structure and the organisation and size of biopores following CCs. ‘Macropores are inversely proportional to the soil compaction’ (Lipiec & Hatano, 2003, p127) therefore, the indirect measurement of macropores can be used to describe changes to soil structure following changes to soil management. CC roots and earthworm activity create stable and persistent macropores and water infiltration can be used as an indicator of preferential flow which is related to the pore size distribution and connectivity (Kutílek, 2004). Water infiltration was tried twice in the research but despite 5 replicates per treatment, the data was not reliable enough to be presented. In one instance the soils were too dry and the placement of the 0.22m dia single ring could not be placed to avoid the large cracks in the soil surface. Secondly, the mini-infiltrometer (Decagon Devices) was used but the soils were still at field capacity and the infiltration permitted through the porous material was too low to allow sufficient water to be infiltrated in a suitable time. Thus, the soil moisture of the field is critical to achieving reliable results with water infiltration. But, farmers would be better able to take measurements at suitable soil moisture contents as they are crop walking more frequently than a trial field 1hr 30mins away.

Aggregate stability is sensitive to CC use in the short term when measured in the laboratory (Liu et al., 2005). An infield aggregate stability method (slake test) has been developed, which is correlated to laboratory based assessments on soil aggregate stability (Herrick et al., 2001). Further investigation and method development may lead to protocols that allow water infiltration and soil aggregate stability to be used in-field as soil quality indicators.

Using the correct soil quality indicators to quantify soil function and soil ecosystem services may be important as the U.K. Government anticipates using public money for public goods, which are provided by beneficial soil management practices (Downing & Coe, 2018). Indicators will need to be chosen with care so that they are sensitive to meaningful change, repeatable, practical, inexpensive and require minimal time. Soil quality indicators whilst used as a tool to implement policy, also foster interest in the farm community. With a standardised set of soil quality indicators and methods, soil management benching marking, such as that seen in the financial performance of farms, would be possible between farms of similar soil type, agro-climate and rotation.

Of the physical and biological soil quality indicators used in this project, some are more suitable than others at detecting the effect of short term CCs. Table 7.2 outlines the suitability of each soil quality indicator for either on-farm assessment or for use in research. Also presented in the table is a relative guide to the time, expense, practicality and sensitivity to detect change for each indicator.

KEY

	✓	✓✓	✓✓✓
Expense[1]	Cheap		Expensive
Time[2]	Quick		Long
Practical[3]	Difficult		Easy
Detect change[4]	Low sensitivity		High sensitivity
On-farm/research	Low suitability		High suitability

[1] Expense includes equipment purchase and/or the costs associated with laboratory and analysis costs.

[2] Time required to sample and analyse the results.

[3] Practical – Are the methods involved easy to carry-out.

[4] Detect change - How sensitive is the method to subtle changes following a CC?

Table 7.2: Recommendation and appraisal of SQI's for use on farm and in research.

Soil Quality Indicator	Expense	Time	Practical	Detect change	On-farm	Research
VESS	✓	✓✓	✓✓✓	✓	✓✓✓	✓✓✓
Bulk density	✓✓	✓✓✓	✓	✓	✓	✓
Penetration resistance	✓✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Soil shear strength	✓✓	✓	✓✓	✓✓	✓✓✓	✓✓✓
Soil moisture	✓✓✓	✓✓	✓	✓✓	✓✓✓	✓
Soil water infiltration	✓	✓✓	✓✓	✓✓	✓✓	✓✓✓
Earthworm abundance	✓	✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Earthworm ecological groups/ species	✓	✓✓	✓✓✓	✓	✓✓	✓✓
Microbial biomass carbon	✓✓	✓✓	✓	✓✓	✓✓	✓
Fungal biomass (Ergosterol extraction)	✓✓	✓✓	✓	✓	✓✓	✓
PLFA	✓✓✓	✓✓✓	✓	✓✓✓	✓✓✓	✓

From experience the combination of VESS with earthworm counts was an efficient use of time. However, I would suggest that VESS is recorded to the nearest 1/3 of a category (Nathan Morris, *personal communication)* as this level of precision rather than whole or half categories may allow the more subtle rotational changes to be detected whilst still maintaining the physical meaning of the scoring system. For example a soil may be in between firm and compact, so a score of 3 and two-thirds, would denote that it was more compact than firm. A digital soil penetrologger was able to detect some differences in soil penetration resistance and it useful to detect tillage pans. However, analogue penetrometers, used on some farms are very unlikely to be able to detect small changes in penetration resistance resulting from CCs in the short term. Bulk density is time consuming to measure, especially at depth and requires post processing of the results. Therefore, its measurement to detect short term changes following CCs would not be recommended. Rather, I think it would be more useful to measure soil infiltration, a key soil function, provided the soil moisture conditions are suitable to allow sufficient measurement. Identification of earthworm species is reliant on the earthworms being adults and so only a small number of the earthworms sampled may be accurately identified depending on the sample.

Finally, when assessing soils following a management change on farm, best practice would be to ensure that there is a control plot to sample from at the same time (e.g. without CC). This will make the detection of meaningful change easier, as it eliminates the variability introduced from the weather which affects CC growth, earthworm lifecycles, soil moisture. Soil moisture and temperature also dictate at what point in the year soils are best sampled, and this may change between years with late summers, wet springs, dry autumns etc.

7.3 Management of Cover Crops

The management of CCs is important for their successful implementation to benefit soil function and in turn deliver soil ecosystems services. Management decisions at all stages of the CC period can affect the outcome, some of which will be guided by the weather and/or policy. Decisions made during this study to improve or mitigate risk in one particular management aspect had consequences for other management decisions, CC growth and effect on soil quality indicators (Table 7.3).

Table 7.3: Reasons for management decisions and their associated consequences

Management decision	Justification	Consequences
Frost sensitive CC	Reduce biomass at time of termination with the view to reduce reliance on glyphosate	Leaching – return of N to the soil before the following crop (maize) is established
	Increase the soil available N at the time of establishment for the following crop (maize)	Unpredictable termination date
		Not a 100% effective termination
Companion crop	Mitigate the risk of difficulties of CC establishment following maize harvest in October	Requires specialist drill
Brassica based CC	Large tap rots to reduce soil compaction	Brassica residues reduced the germination of the following companion crop
Use of mixtures	Variety of root and growth traits to improve soil quality indicators	Different CC species with different seed sizes require specific seeding depths
		Small seeds planted too deep and fail to germinate

Currently there is a reliance on non-selective herbicides (e.g. glyphosate) to terminate CCs and also some concern amongst U.K. farmers about N immobilisation following CCs (Storr et al., 2019; White et al., 2016). Using a frost sensitive CC that senesces due to cold temperatures may increase the N available to the following crop and also help reduce the reliance on glyphosate that may have its license for use withdrawn in the future (European

Commission, 2018). However, these benefits can be unreliable because CC senescence due to cold temperatures is unpredictable and not 100% effective. Alternative termination methods may be more expensive such as using other chemical products; or less effective such as the use of roller crimpers and flailing (Vincent-Caboud et al., 2017). Furthermore, roller crimpers and flailing machinery have a reduced working width compared to a sprayer and will require an increased area of the field to be trafficked at a time in the year (late winter/ early spring) when the soils are at or near field capacity and therefore, increase the risk of soil compaction (Mapfumo & Chanasyk, 1998). On farm trials are currently underway to assess the effectiveness and improve the management of these alternative CC termination methods with the Innovative Farmers programme (Soil Association, 2015).

The establishment of the second CC period as a companion crop was troublesome. Following maize harvest in October it may be difficult to establish a CC due to poor soil conditions following harvest traffic if it is particularly wet and also CC growth would be limited with the declining temperature and sunlight hours. Thus, it was decided to establish a companion crop with the maize. However, the practical knowledge regarding companion crops is limited in the UK: general companion cropping is part of the international DIVERSify project, whilst companion crops with maize has been researched at Reaseheath College (European Unions Horizon 2020, 2017; Reaseheath College, 2016). Often a specialist drill is required that is capable of establishing two crops with different seed sizes. For optimum germination these may need to be sown at different depths and also down different coulters to avoid competition between the crops. Such drills are expensive, and modification of existing machinery would require specialist knowledge and skills.

Legumes have a small seed and require a shallow establishment (5mm) (Ogle & St. John, 2009). The drill depth used in this study when establishing the CC and companion crop seed mixture was 25mm. Thus, legume establishment in both the winter hardy CC and companion crop mixtures was poor (Appendix C, Appendix G). The small-seeded legumes would possibly benefit from being established separately from the rest of the mixture, although this is technically difficult as extra hoppers and coulters on the drill would be required, which may not be feasible and also adds to the expense of the machine. Alternatively, this could be achieved by a standalone broadcasting unit that is fitted to an existing piece of machinery/tractor, but this method would reduce the accuracy of seed placement and germination. CC mixtures with different seed sizes and thus different drilling depth requirements need careful consideration so that money is not wasted on seeds that fail to germinate due to incompatible seeding depths.

The companion crop that was established with the maize was affected by the preceding CC choice. Growth of the companion crop was poor following the high brassica content CC mixtures when compared to the control plots (Haramoto & Gallandt, 2004) (Appendix G). In order to accumulate and increase the benefits associated with the second CC period it will be necessary to consider the effect of the preceding CC species choice on the following CC. The effect of CC species is often considered for the following cash crop, but this study highlights the need to also consider its effect on any following plant species established whether they are a CC or cash crop.

7.4 Policy Incentives

Changes to agricultural policy are imminent and there is a desire to pay farmers for public goods (Downing & Coe, 2018). The Basic Payment Scheme allows farmers to use CCs to fulfil their requirements for Greening but are constrained by the CC species used and the dates in which they have to remain in place (Rural Payments Agency, 2016). The survey conducted as part of this project revealed that 71% of respondents did not think that the rules (Basic Payment Scheme 2016) that govern CC use were suitable. Farmers using CCs suggested that the number of CC species allowed should be increased – this option would also lead to some non-users of CCs to trial them too. Additionally, being allowed to graze CCs was also a suggestion. Grazing CCs may provide an alternative method of CC termination which would be particularly important if glyphosate is withdrawn from use. Furthermore, grazing CCs may encourage the diversification of arable farms which would have benefits for soil quality and ecosystem services (Lemaire et al., 2014). However, the grazing of CCs on horticultural farms may be more problematic as food safety standards do not allow CCs to be grazed immediately prior to leafy salad crops (Litterick, 2018). Some water companies recognising the role of CCs to reduce nitrate leaching and soil erosion have introduced their own initiatives to encourage CC establishment and will consider any CC species and also allow the CCs to be grazed after a certain date. (Severn Trent Water, 2018).

Recognising the benefit of the ecosystem services that CCs provide (e.g. water quality), national policy may either make CCs mandatory as they are in France or, pay farmers for the public services CCs provide. CCs are unlikely to have an immediate financial benefit (increased yield) to the farmer; yet there are establishment and termination costs associated with CCs as well as the risk of negatively affecting the following crop if not managed correctly. Therefore, farmers, at least initially, whilst they adapt to new management practices and the soil quality benefits accumulate (and increase crop yield) are likely to welcome any financial assistance to establish CCs.

Ecosystem services reflect soil function which is measured by soil quality indicators that can be measured on farm or at catchment level. Not all changes to soil quality indicators due to CCs are easy to measure as they are subtle and may occur over many years. However, N is easy to measure relative to other soil quality indicators and it can be valued by i) N cycling benefit to the farmer at an equivalent mineral nitrogen replacement cost and ii) costs associated with improving water quality at treatment plants due to N leaching. Loss of top soil due to erosion also has a value too in its i) replacement value and ii) cost of removal as sediment from water. In the U.S., Roth *et al.,*(2018) used soil erosion, N loading and potential N cycling for the evaluation of CCs, and concluded that autumn sown CCs recovered 86% of their costs – the majority of the cost recovery (70%) being due to N mineralization from the CC. In the U.K. the subsidy that water companies place on CCs is variable, with £60 and £110 ha^{-1} offered to farmers in the catchments of Severn Trent Water (2018) and South Staffs Water (2018), respectively. The difference in subsidy received is related to what a water company believes is it's fair share to pay to tackle water pollution. For instance Severn Trent Water, guided by the Environment Agency, pay 50% of the actual value of CC establishment and management (£120 ha^{-1}) as its fair share with the remaining 50% agriculture's fair share (Alex Cooke, *personal communication*). Some water companies, such as South Staffs Water and Anglian pay a greater subsidy as that is perceived to be the only way to engage the farming community.

Financial incentives to fairly compensate farmers for their contribution to ecosystem services and the use of policy that is flexible (CC species, termination management, etc) will encourage the implementation of CCs by farmers. Flexible policy options will allow farmers to tailor CC species and management to their rotation, soil type and geographic region for the benefit of not only themselves but to wider ecosystem services.

7.5 Limitations of the Research

7.5.1 Survey

The main limitations of the survey were the potential bias in the distribution from the author's Twitter account (only reaching farmers that may be active on Twitter and practice sustainable agriculture) and the limited number of respondents. Should the survey be repeated then a reduced number of questions and a variety of distribution methods that appeal to a wider farming demographic would help to increase the quality of data collected.

7.5.2 Field Trials

Replication of field trials is always going to be a challenge because of the time and space required. Whilst it was possible to repeat phase 1 in a different field the following year, the repetition of phase 2 was not possible. Replication may be possible over time (e.g. two replicates of the rotation following each other) or space (the same rotation running simultaneously in a different field). The number of replicates sampled per treatment, although sufficient at Prickwillow to conduct the minimum number of VESS assessments (5) could have been improved by sampling all the replicates created (9), which would have allowed blocked statistical analysis of the trial. Additionally, in order to allow the ease of machinery operations complete randomisation of the treatments could not be achieved.

The control plots associated with both phase 1 experiments grew with wheat volunteers. The growth of the wheat volunteers was un-intended and the large biomass of the wheat volunteers was not expected. Recognising the issue in the first year of the trials (Prickwillow, phase 1), a plan was in place to eradicate wheat volunteers with herbicide in the repetition of phase 1 at Littleport. Unfortunately, due to farm operations in autumn 2017 this did not occur. With wheat volunteers present in the control, the comparison to the CC treatment became much more difficult. Both the control and the CC treatment had active roots in the soil profile that only differed by root architecture. Nevertheless, the growth of wheat volunteers in the control, is still a valuable comparison to CCs, as some farmers may not terminate volunteer crops between cash crops and consider them as a cheap alternative to purchased CC seed.

Representative yield assessment at field scale is difficult. The pressure of commercial agriculture, use of contractors and trial plot layout (especially at Prickwillow) meant it was not possible to harvest and weigh entire trial plots over a weighbridge. As in other research, 2 rows of 10 maize plants were harvested and used to calculate maize yield.

Commercially, lettuce yield or predicted harvestable lettuce heads is assessed using Agri-Eye - an image analysis (collected via a plane) algorithm that classifies lettuce head size to 5 categories (developed by G's Growers Ltd.). Combined with GPS, this would have allowed for the assessment of harvestable lettuce sizes in each plot of the Prickwillow trial. Unfortunately, during the period that the lettuce was grown on the trial, the plane was grounded due to civil aviation authority regulation and the third party asked to collect the images using drones lost the data collected. Therefore, lettuce yield was assessed according to mass, with 10 lettuces from each of the selected plots. Additionally, after lettuce yield sampling it became apparent that three lettuce varieties had been planted from the 21st – 25th June 2018. Had this information been obtained earlier, it would have been possible to plan and harvest lettuce according to days after planting, and not a fixed date. To this end, lettuce yield results are a guide at best.

7.6 Recommendations for Further Research

There are numerous options for further CC research that would aid understanding of their effect on soil quality indicators and management.

7.6.1 The Effect of Cover Crops on Pest and Disease

Whilst CCs were investigated for their effect on soil quality indicators, it was beyond the scope of the research to consider the effect of CCs on pests (slugs) and disease. CCs may increase the slug population and/or increase disease carry-over. Whilst CCs provide ecosystem services (improve water quality by mitigating nitrate leaching) if they increase slug populations or disease then more slug pellets or fungicides/ insecticides may be used. Thus, the effect of CCs on slug population and disease should be investigated and also management options proposed.

7.6.2 Cover Crop Termination

Non-selective herbicide is a popular method of CC termination, but the license required to use glyphosate may be withdrawn in the future. Therefore, the evaluation of different CC termination techniques and their effect on soil quality indicators would enable farmers to perhaps consider other means of CC termination, reducing the reliance on herbicide. This will require an understanding of the growth characteristics of the CC and the growth stage at which it is most susceptible to mechanical damage or cold temperatures to ensure a reliable termination.

7.6.3 Effect of Companion Crops

Companion crops established with cash crops (maize, oilseed rape and carrots) are an emerging practice in the U.K. Evaluation of the effect of companion crops on both the cash crop it is sown with and soil quality indicators would provide knowledge to a niche technique of crop establishment in the U.K. There will also be practical considerations of how to establish and terminate the companion crop.

7.6.4 Effect of Intensive Tillage

In purely combinable crop rotations it is possible in many circumstances to completely avoid soil disturbance and use CCs to provide continuous plant cover, which allows the benefits to soil quality to accumulate. However, many rotations include crops that require intensive soil preparation for either establishment or harvest (potatoes, sugar beet, salad and vegetable crops) and when grown in rotation with combinable crops, rotational tillage will be feature of the soil management practice of the farm. The investigation of the effect of intensive tillage following a period of minimal tillage and CCs would add to our understanding of the changes taking place to soil quality indicators throughout a rotation. Specifically, are the benefits associated with CC use earlier in the rotation completely lost, or can CCs provide resilience to soil quality indicators compared to bare soil.

7.6.5 Nitrate Leaching

Whilst a lot is known about N leaching and the measures required to prevent it from occurring, the use of frost sensitive CC species that begin to senesce mid-Winter may reduce the N leaching control afforded by a CC. Research to establish the N leaching potential of frost sensitive CCs over mid-Winter would ensure that N leaching is not excessive with early and unpredictable senesce of a CC.

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APPENDICES

Appendix A Sampling Timeline

Table A-1: Operations and sampling timeline for the trials undertaken at Prickwilow.

Date	Actions undertaken at trial site
2016	
14 Aug	**Wheat harvest**
26 Aug	**40m^3 ha^{-1} digestate liquor applied to the trial site**
26 Aug	**Cover crops established**
9 Dec	Install soil moisture access tubes
2017	
5 Jan	Commence weekly measurement of soil moisture
19 Mar	Cover crop biomass assessment
7 Apr	**Glyphosate applied to trial area**
28 Apr	Commence soil sampling
3 May	Finish soil sampling and remove soil moisture access tubes
11 May	**Tillage to 0.08m across trial area**
	Establishment of maize and companion crop
4 Oct	Maize yield assessment
11 Oct	**Maize harvest**
23 Oct	Cover and companion crop establishment counts and biomass
18 Dec	Install soil moisture access tubes
2018	
4 Jan	Commence weekly soil moisture measurements

19 Mar	Commence soil sampling
22 Mar	Finish soil sampling
3 May	Soil sample for microbial analysis
21-25 Jun	**Lettuce transplanted**
31 Jul	Lettuce yield assessment
1-3rd Aug	**Lettuce harvest**

Table A-2: Operations and sampling timeline for the trials undertaken at Littleport.

Date	Actions undertaken at trial site
<u>2017</u>	
12 Aug	**Wheat harvest**
24 Aug	**Cover crops established**
4 Sept	Soil sample
18 Sept	Soil and aboveground biomass sample
9 Oct	Soil and aboveground biomass sample
23 Oct	Cover and companion crop establishment counts and biomass
31 Oct	Soil and aboveground biomass sample
21 Nov	Soil and aboveground biomass sample
13 Dec	Soil and aboveground biomass sample
18 Dec	Install soil moisture access tubes
<u>2018</u>	
4 Jan	Commence weekly soil moisture measurements
	Soil and aboveground biomass sample
24 Jan	Soil and aboveground biomass sample
14 Feb	Soil and aboveground biomass sample
7 Mar	Soil and aboveground biomass sample
19 Mar	Commence soil sampling
22 Mar	Finish soil sampling
28 Mar	Soil and aboveground biomass sample
4 Apr	Soil sample for microbial analysis

6 Apr	Volunteer count
12 Apr	Soil and aboveground biomass sample
21 Apr	**Glyphosate applied to trial area**
25 Apr	Soil and aboveground biomass sample
10 May	Soil and aboveground biomass sample
20 May	**Maize planted**
3 Oct	Maize yield assessment
12 Oct	**Maize harvest**

Appendix B Companion Crop Trial 2016

Following forage maize (variety not known) establishment in 2016 a replicated trial was set up to investigate four companion crop treatments with the use of: Tall Fescue (TF) ‘Kora’, perennial rye grass (PRG) ‘Foxtrrot’ and yellow trefoil (YT) in different combinations. The two grasses were established as ‘straights’ at 8 kg ha^{-1} and each as a mixture with the yellow trefoil. The mixtures were sown at 4.8 Kg ha^{-1} for the grass species and 6 kg $ha^{-1}$for the yellow trefoil, These four treatments were compared to a bare control.

Maize was established on 17th May 2016 and received one herbicide application on the 16th June 2016 and an application of slug pellets on the 22nd June 2016. These operations were carried out by the host farm with the agronomic interventions recommended by a BASIS qualified agronomist. On the 24th June 2016 at maize leaf stage 5, the 4 companion crop treatments were broadcast using a hand-held applicator. Plot size was 8mx12m. On the 28th July, companion crop establishment was measured using a 0.25m^2 quadrat. The results of the establishment counts are shown in Table B-1.

Table B-1: Mean establishment count of companion crop species (TF = tall fescue, PRG = perennial rye grass and YT = yellow trefoil) and weed (count m^{-2}). n =3.

Treatment	Grass (count m^{-2})	Legume (count m^{-2})	Weed (count m^{-2})
Control	-	-	56
PRG	220	-	20
TF	68	-	48
PRG + YT	108	212	20
TF + YT	88	264	24

Establishment of TF as a straight was poor compared to that of the PRG, however the mixture of TF and YT has a similar establishment to that of the PRG and YT mixture. Following this trial, a drill suitable for establishment of the companion crop simultaneously with maize was found for the trial in 2017 (phase 2). With better establishment expected from the placement of the seed by drill rather than broadcasting the decision was made to select TF rather than PRG. Additionally, it was decided that YT was too vigorous in growth and may have competed with the maize, therefore, it was deemed too risky to establish at field scale. Thus, YT was substituted for white clover and the selected mix for phase 2 was TF + white clover.

Appendix C Cover Crop Establishment

Following the establishment of the two different CC mixtures, plant counts were conducted in autumn 2016 using a $0.25m^2$ quadrat. Plant counts for the winter hardy (Table C-1) and frost sensitive (Table C-2) CC mixtures are given below.

Table C-1: Cover crop species counts per m^2 for the winter hardy mixture.

Species	Forage rye	Oilseed radish	Berseem clover
Count	15	7	2

Table C-2: Cover crops species counts per m^2 for the frost sensitive mixture.

Species	Black oats	Oilseed radish	White mustard
Count	84	25	12

Appendix D Cover Crop Survey Questions

Sustainable Soil Management Survey

Start of Block: Introduction

Q1.1
Sustainable Soil Management Survey

The aim of this survey is to understand the implementation and management strategies of cover crops as part of sustainable soil management approaches to crop production across the United Kingdom. The information will be used as part of a PhD project to help inform cover crop use, understand the reasons why cover crops may or may not be used, and provide a guide for future research. I will also ask for general information on crop establishment and soil health.

The survey has been developed by a PhD student at Cranfield University to inform research on sustainable soil management and cover crops in the UK. The data collected in this study will be used to supplement the research of a PhD project studying sustainable soil management strategies. All data collected will be stored in accordance with the UK Data Protection Act (1998) in a secure folder only accessible by Cranfield University staff. All information will be treated with the strictest confidence. Participants will only be identifiable to the researcher (Tom Storr) if they have indicated their wish to be so. Research findings may form the basis of publications and presentations, but no participating individuals/ organisations will be named or identifiable.

Participants are free to withdraw their data without explanation by emailing the PhD researcher Tom Storr (tom.storr@cranfield.ac.uk) at any point. If you have any questions about the research, or how your data will be used please do not hesitate to contact Tom Storr.

By continuing with the questions you confirm that you have read and fully understand the information provided above, and therefore give your consent to taking part in this research.

○ Continue to survey (1)

End of Block: Introduction

Start of Block: Farm Information

Q2.1 Farm type

○ Combinable crops (including grass) (2)

○ Non - combinable crops (salads, vegetables, sugar beet, potatoes) (1)

Q2.2 Are livestock present on the farm

○ YES (1)

○ NO (2)

Display This Question:

If Are livestock present on the farm = YES

*

Q2.3 Type of livestock
(multiple answers may be selected)

▢ Beef (1)

▢ Dairy (2)

▢ Pigs (3)

▢ Poultry (4)

▢ Sheep (5)

▢ Other (please specify) (6) ____

Q2.4 Farm area managed

○ Ha (1) ____

Q2.5 Annual average rainfall

○ mm (1) ____

Q2.6 Please select the region where the farm is predominately based

○ East Anglia (1)

○ East Midlands (2)

○ London (3)

○ North East England (4)

○ North West England (5)

○ South East England (6)

○ South West England (7)

○ West Midlands (8)

○ Yorkshire and the Humber (9)

○ Northern Ireland (10)

○ Scotland (11)

○ Wales (12)

Q2.7 Please enter the first part of the postcode for where the farm is predominately based This is so answers can be more accurately mapped E.g MK16

____

Q2.8 Select the soil texture that is most dominant on the farm

▼ Organic soils (organic layer > 41cm) (1) ... Silt loam (13)

End of Block: Farm Information

Start of Block: Crop Establishment Information

Q3.1 How are/will the crops for harvest 2017 be established (Multiple answers may be selected for the establishment operation)

Where appropriate please indicate whether the crop is a winter or spring sown variety. E.g Winter wheat Please include grass Tillage definitions: Deep tillage – Tillage to a depth greater than 7 cm (3 inches)
Shallow tillage – Tillage to a depth less than (or equal to) 7 cm (3 inches)
Direct drill - Sowing of crops directly into the residues of the previous crop with tillage operations
Strip till – cultivates a band of soil, but still retaining crop residue and undisturbed soil
Zero till – At least 70% of the soil surface undisturbed with residue from the previous crop left on the surface

	Organic		Establishment									Area (Ha)	Crop
	Yes (1)	No (2)	Plough (1)	Power harrow (2)	Sub soil (3)	Deep tillage >7cm (4)	Shallow tillage =	Direct drill (6)	Strip till (7)	Zero till (8)	Broadcast (9)	(1)	(1)
Crop 1 (1)	○	○	○	○	○	○	○	○	○	○	○		
Crop 2 (2)	○	○	○	○	○	○	○	○	○	○	○		
Crop 3 (3)	○	○	○	○	○	○	○	○	○	○	○		
Crop 4 (4)	○	○	○	○	○	○	○	○	○	○	○		
Crop 5 (5)	○	○	○	○	○	○	○	○	○	○	○		
Crop 6 (6)	○	○	○	○	○	○	○	○	○	○	○		
Crop 7 (7)	○	○	○	○	○	○	○	○	○	○	○		
Crop 8 (8)	○	○	○	○	○	○	○	○	○	○	○		

Q3.2 Have cover crops been established following crops harvested in 2016? These cover crops may have been undersown/ interseeded in to the crop harvested

○ YES (1)

○ NO (2)

End of Block: Crop Establishment Information

Start of Block: No Cover Crops

Q4.1 Which statement best describes your experience with cover crops

○ Never used cover crops (1)

○ Previously used cover crops, but no longer use them (2)

Display This Question:

If Which statement best describes your experience with cover crops = Previously used cover crops, but no longer use them

Q4.2 For how many seasons did you use cover crops before you stopped using them?

○ 1 year (1)

○ 2- 5 years (2)

○ 5 years + (3)

Q4.3 Cover crops are not/ no longer used because
Rank the top **3** reasons, with **1** the main reason

______ Concern they will become a weed (1)

______ Concern of the effect on the following crop yield (2)

______ Concern with disease (green bridge) (3)

______ Concern with pests (4)

______ Do not have management control of the land for long enough to realise their potential benefit (5)

______ Do not have the correct machinery to implement their use (6)

______ Expense (7)

______ Hard to measure their benefit (8)

______ Lack/ confusion of information about different species/ varieties (9)

______ Lack/ confusion of information about cover crop management (10)

______ They do not fit the current rotation (11)

______ Use of time and labour (12)

______ Other (please specify) (13)

Display This Question:

If Cover crops are not/ no longer used becauseRank the top 3 reasons, with 1 the main reason [Do not have management control of the land for long enough to realise their potential benefit] Is Not Empty

Q4.4 For how long is the land under your management control

○ 1 year (1)

○ 2-5 years (2)

○ 6-10 years (3)

○ 11 years + (4)

○ Prefer not to answer (5)

Q4.5 Would you consider using cover crops in the future?

○ YES (1)

○ Maybe (2)

○ NO (3)

Skip To: End of Block If Would you consider using cover crops in the future? = NO

Q4.6 What measures would influence your adoption of cover crops Rank the top 3 reasons, with 1 the main reason

_______ Access to the correct machinery (1)

_______ Access to funds/grants to help with seed purchase or establishment costs (2)

_______ More detailed information on cover crop species (3)

_______ More detailed information on the economics of cover crops (4)

_______ More detailed information on the effect of cover crops and how to measure this on the farm (5)

_______ More research into cover crops by the agricultural industry E.g. Seed companies, agronomy companies (6)

_______ More independent research into cover crops E.g Universities, NIAB, ADAS (7)

_______ Opportunity to establish free or subsidized cover crop seed on the farm as a trial (8)

_______ Change in regulation of the cover crop species that are included as an Ecological Focus Area cover/catch crop (9)

_______ Change in regulation of the dates when an Ecological Focus Area cover/catch crop must be established by and remain in the ground until (10)

_______ Seeing neighbours successfully using cover crops (11)

_______ Other (please specify) (12)

End of Block: No Cover Crops

Start of Block: Cover Crops

Q5.1 Including 2016, how many seasons have cover crops been used
▼ 1 year (1) ... 10 years + (10)

Q5.2 Total area of cover crops planted in 2016

○ Ha (1) ____

Q5.3 Are the current Ecological Focus Area (Greening) definitions of cover/ catch crops suitable

○ YES (1)

○ NO (2)

Display This Question:

If Are the current Ecological Focus Area (Greening) definitions of cover/ catch crops suitable = NO

Q5.4
How would you like to see the Ecological Focus Area definition of cover/ catch crops changed?

____

____

____

____

____

Q5.5 Are cover crops planted on rented land?

- YES (1)
- NO (2)
- Land is not rented (4)
- Prefer not to answer (3)

Display This Question:

If Are cover crops planted on rented land? = YES

Q5.6 For how long is the land under your management control

- 1 year (1)
- 2 - 5 years (2)
- 6 - 10 years (3)
- 11 years + (4)
- Prefer not to answer (5)

Q5.7 Initially cover crops were trialled on a small part of the farm?

- YES (1)

◯ NO (2)

Q5.8 What are your reasons for using a cover crop?
Rank the top **3** reasons, with **1** the main reason

_______ Fix nitrogen (1)

_______ Fulfilment of the Ecolgical Focus Area greening measures (2)

_______ Improve movement of water through the soil (3)

_______ Improve soil biology (4)

_______ Increase soil organic matter (5)

_______ Reduce compaction (6)

_______ Resilience to extreme weather (7)

_______ Scavenge nutrients in the soil (8)

_______ To combat soil erosion (9)

_______ To manage weeds (10)

_______ To provide habitat and food source for wildlife (11)

_______ To reduce pest pressure (e.g biofumigant/ nematode reducing) (12)

_______ Other (please specify) (13)

Q5.9 The cover crops used are predominately

◯ Single species (1)

◯ Contain 2-3 species (2)

◯ Contain 4 + species (3)

Q5.10 Seed Origin

◯ Seed supplier (1)

◯ Farm saved seed (2)

○ Mixture of farm saved seed and that of a seed supplier (3)

Display This Question:

If The cover crops used are predominately != Single species

Q5.11 Cover crop preparation

○ Pre-packaged and formulated cover crop mixtures from industry suppliers (1)

○ Custom mixtures that a seed supplier prepares for me (2)

○ I prepare my own mixture on farm (3)

Q5.12 The cover crop species used were

○ My decision alone (1)

○ Advised by a seed rep/agronomist (2)

○ Advised by a farming friend/ neighbour (3)

○ A mix of the above (4)

Q5.13 Knowledge of cover cropping is derived fromSelect the **3** most relevant. At least 2 responses required

▢ Agronomist (1)

▢ Farming Press e.g. Farmers Weekly (2)

▢ Forums e.g The Farming Forum (3)

☐ Industry events e.g Cereals, Trial open days, GroundswellAG, GREATsoils event (4)

☐ Internet sources (5)

☐ Scientific publications (6)

☐ Social media e.g. Twitter (7)

☐ Visiting other farmers (8)

☐ Other (Please Specify): (9)
____

Q5.14 What are the most important attributes you want from a cover crop Rank the top 3 attributes, with 1 the most important attribute

_______ Biofumigant (1)

_______ Breaks down quickly (low C:N ratio) (2)

_______ Fibrous roots (3)

_______ Frost sensitive (4)

_______ Nitrogen fixing (5)

_______ Nutrient scavenging (6)

_______ Nematode reducing (release of exudates) (7)

_______ Tap roots (8)

_______ Winter hardy (9)

_______ Other (Please specify): (10)

Q5.15 Challenges of using cover crops

	Always an issue (1)	Sometimes an issue (2)	No longer an issue (3)	Has never been an issue (4)	I don't know (5)
Cover crop biomass following termination (1)	○	○	○	○	○
Cover crop establishment (2)	○	○	○	○	○
Cover crop uses too much moisture (3)	○	○	○	○	○
Effective termination (4)	○	○	○	○	○
Increase disease (5)	○	○	○	○	○
Increase pests e.g. slugs (6)	○	○	○	○	○
Nitrogen immobilization (7)	○	○	○	○	○
Time and labour required (8)	○	○	○	○	○
Yield reduction in following crops (9)	○	○	○	○	○

Q5.16 Management of a challenge you may have faced using cover crops
Please provide a brief description of the challenge(s) you faced and how you managed the challenge.
Or use this space to highlight any other challenges you have encountered using cover crops.
E.g. Single species of mustard pre potato establishment which resulted in too much biomass, blocking the destoner – now use a cover crop containing rye, oats and mustard which produces a smaller biomass, flowing through the destoner better.

____

____

____

____

____

Page Break

Q5.17 What, if any, differences to the soil environment have there been since using cover crops

	Positive change (1)	Negative change (2)	No change (3)	Don't know (4)
Soil structure (1)	○	○	○	○
Drainage/ infiltration of water (2)	○	○	○	○
Organic matter (3)	○	○	○	○
Soil nutrient availability (4)	○	○	○	○
Soil colour (5)	○	○	○	○
Soil erosion/ water runoff (6)	○	○	○	○
Number of soil working/trafficable days (7)	○	○	○	○

Q5.18 What, if any, differences have there been to the following

	Increase (1)	Decrease (2)	No change (3)	Don't know (4)
Weed population (1)	○	○	○	○
Slug population (2)	○	○	○	○
Worm population (3)	○	○	○	○

Q5.19 Since using cover crops how have the following changed

	Increase (1)	Decrease (2)	No Change (3)	Don't know (4)
Fuel use (1)	○	○	○	○
Use of chemical fertilisers (2)	○	○	○	○
Use of herbicides (3)	○	○	○	○
Use of slug pellets (4)	○	○	○	○

Q5.20 Have cover crops had an effect on yield

○ Yes, Increase (1)

○ Yes, Decrease (2)

○ No change (3)

○ Don't know (4)

Skip To: End of Block If Have cover crops had an effect on yield = No change

Skip To: End of Block If Have cover crops had an effect on yield = Don't know

Q5.21 For a specified crop, how much would you estimate the yield difference to be due to cover crops
Please move to the next question if you are unsure

○ Crop (1) ____

○ t/Ha (2) ____

End of Block: Cover Crops

Start of Block: Cover Crop Management

Q6.1 Where in the rotation is the largest area of the same cover crop sown
E.g.
Crop harvested 2016 pre cover crop: Winter Wheat
Crop to be planted post cover crops: Spring Barley

- ○ Crop harvested 2016 pre cover crop (1) ____
- ○ Crop to be planted post cover crop (2) ____
- ○ Area of cover crop planted in this rotation (Ha) (3) ____

Q6.2 Please provide the following details about this cover crop

- ○ Seed rate (Kg/Ha) (1) ____
- ○ Cost of Seed (£/Ha) (2) ____

Q6.3 What are the species used in this cover crop. Please rank by largest % first (must sum to 100)

NB. if a standard industry mix is used then please give the name of this in the 'cover crop species #1' box and ensure a '100' is written in the percentage box.
Otherwise fill as example below:
Black oats 50

Vetch 30
Oilseed radish 15
Mustard 5

	Percentage of species in the cover crop (%) (1)
⊗Cover crop species #1 (1)	

⊗Cover crop species #2 (2)

⊗Cover crop species #3 (3)

⊗Cover crop species #4 (4)

⊗Cover crop species #5 (5)

⊗Cover crop species #6 (6)

⊗Cover crop species #7 (7)

⊗Cover crop species #8 (8)

Q6.4 How is the harvested crop residue managed

○ Baled (1)

○ Chopped (2)

○ Chopped and straw raked (3)

○ Tall stubble is left e.g. stripper header (4)

○ Residue left on surface (veg/salad) (5)

Q6.5 When is the cover crop established

○ Before crop harvest 2016 (undersown/interseeded) (1)

○ After crop harvest 2016 (3)

Display This Question:

If When is the cover crop established = Before crop harvest 2016 (undersown/interseeded)

Q6.6 More specifically when was the cover crop undersown/interseeded with the crop that was harvested 2016?

○ At the same time as crop establishment (1)

○ Within 6 weeks of crop establishment (2)

○ Within 6 weeks of crop harvest (3)

○ Other (Please specify): (4)
____

Q6.7 What operations were used to establish the cover crop (Multiple answers may be selected)

Tillage definitions: Deep tillage – Tillage to a depth greater than 7 cm (3 inches) Shallow tillage – Tillage to a depth less than (or equal to) 7 cm (3 inches) Direct drilling - Sowing of crops directly into the residues of the previous crop with tillage operations Strip tillage – cultivates a band of soil, but still retaining crop residue and undisturbed soil Zero tillage – At least 70% of the soil surface undisturbed with residue from the previous crop left on the surface Slurry/digestate application - seed mixed with slurry/ digestate

▢ Plough (1)

▢ Power harrow (2)

▢ Sub soil (3)

▢ Deep tillage >7cm (4)

▢ Shallow tillage = (5)

▢ Direct drill (6)

▢ Strip till (7)

▢ Zero till (8)

- [ ] Broadcast (9)
- [ ] With slurry/ digestate application (10)

Q6.8 How will the cover crop be terminated Up to **2** answers maybe selected. E.g. grazing followed by herbicide

- [ ] Cultivation (1)
- [ ] Grazed (2)
- [ ] Herbicide (3)
- [ ] Mow/ flail (4)
- [ ] Natural senescence (5)
- [ ] Plough (6)
- [ ] Roller crimper (7)
- [ ] Other (please specify): (8) ____

Q6.9 If cover crop termination is indicated by 0, use the slider to indicate when the following crop will be sown

Crop Establishment (1)

Q6.10 If cover crops are grown else where in the rotation, please state the crops between which they occurMove to the next question if this does not apply

	Rotation 1 (1)	Rotation 2 (2)	Rotation 3 (3)
Crop pre cover crop (1)			
Crop post cover crop (2)			

End of Block: Cover Crop Management

Start of Block: Soil

Q7.1 In your own words define soil health
No more than 4 sentences

____

____

____

____

____

Q7.2 Generally, how is the soil environment assessed

	Do you use this method of assessment	
	Yes (1)	No (2)
⊗Farm walk visual observations E.g appears less soil erosion (1)	○	○

⊗Spade Observations 'Dig a hole and have a look' (2)	○	○
⊗Observations and assessment using a prescribed method E.g. Visual Evaluation of Soil Structure, Visual Soil Assessment, infiltration rings etc (3)	○	○
⊗Soil samples taken and sent off for analysis (4)	○	○

Q7.3 In general, are the assessments of soil

○ Sporadic and random across the farm (1)

○ Conducted at regular intervals evenly across the farm (2)

Q7.4 Would you be interested in learning about soil health and/or methods that can be used to assess soil health

○ Yes (1)

○ No (2)

Display This Question:

If Would you be interested in learning about soil health and/or methods that can be used to assess s... = Yes

Q7.5 How would you like to learn these methods
Select the **3** most relevant. At least **2** responses required

▢ Attendance at free events/ courses. E.g GREATsoils events, AHDB monitor farms (1)

- [ ] Attendance on a paid course/ event E.g. Innovative Farmers (2)
- [ ] Farming magazines (3)
- [ ] Online. E.g Youtube, blogs, articles (4)
- [ ] Scientific/ University publications (5)
- [ ] Through my agronomist (6)
- [ ] Other (Please specify): (7) ____

Q7.6 Are you currently receiving advice and/or actively self-learning about soil health

- ○ Yes (1)
- ○ No (2)

Display This Question:

If Are you currently receiving advice and/or actively self-learning about soil health = Yes

Q7.7 How are you currently receiving advice/ learning about soil healthSelect the **3** most relevant. At least **2** responses required

- [ ] Attendance at free events. E.g GREATsoils events, AHDB monitor farms (1)
- [ ] Attendance at paid for courses or events E.g Innovative Farmers (2)

- ☐ Farming magazines (3)
- ☐ Online. E.g Youtube, blogs, articles (4)
- ☐ Scientific/ University publications (5)
- ☐ Through my agronomist (6)
- ☐ Other (Please specify): (7) ____

Q7.8 Are there any trials taking place on your own farm relating to soils/ cover crops/ crop rotation/ tillage

- ○ Yes, I conduct my own trials (1)
- ○ Yes, an outside organisation is involved too. E.g University, agronomy company (2)
- ○ No (3)

End of Block: Soil

Start of Block: Other

Q8.1 Participant age

- ○ 25 and under (1)
- ○ 26 - 35 (2)
- ○ 36 - 45 (3)
- ○ 46 - 55 (4)

○ 56 - 65 (5)

○ 66 and over (6)

Q8.2 Prize draw - 2 tickets for Groundswell 2017
If you wish to be entered into the prize draw for completing this questionnaire please leave contact details
Prize draw 13th March 2017
Winner to be notified by email/telephone

○ Name (1) ____

○ Email (2) ____

○ Phone (3) ____

Q8.3 Using the details given above for the prize draw are you happy for the researcher to contact you regarding

	YES (1)	NO (2)
Answers given that are of particular interest (1)	○	○
Your involvement in University research E.g Field trials, soil samples (2)	○	○
A copy of the general survey results (3)	○	○

Q8.4 Additional comments
This space is for you to provide any further comments, thoughts or ideas relating to this survey or more generally about soils and cover crops.

____
_

End of Block: Other

Appendix E VESS Photographs

Below are photographs of blocks of soil extracted from phase 1, Prickwillow in 2017 and their assigned VESS score.

Figure E-1: VESS score 2

Figure E-2: VESS score 2.5

Figure E-3: VESS score 3

Figure E-4: VESS score 3.5

Appendix F Root Data

For each species, five plant roots were randomly sampled to 0.15m depth from across all plots at Littleport phase 1 using a bi-partite root corer of 0.08m dia. (Eijkelkamp, The Netherlands). Roots were thoroughly washed of soil using tap water. Measuring cylinders were used to calculate water displacement of the roots to give an approximation of root volume (m^3). Roots were then dried at 65°C for 48hrs before weighing and determination of their mass (g). Root volume and mass are shown in Table F-1.

Table F-1: Root characteristics of the individual species of the frost sensitive cover crop and the wheat volunteers of the control. Values in parenthesises denote SEM. Significant differences, per characteristic, are denoted by different letters.

Plant species	Mustard	Black oat	Oilseed radish	Wheat volunteers
Mass (g)	1.8^{b} (0.31)	0.1^{a} (0.01)	0.9^{ab} (0.458)	0.2^{a} (0.019)
Volume ($x10^{-6}$ m^3)	11.6 (1.83)	1.5 (0.21)	13.0 (6.4)	2.5 (0.27)

Appendix G Phase 2 Companion Crop Growth

Companion crop establishment count and biomass was assessed in autumn 2017 following maize harvest using a 0.25m^2 quadrat. Companion crop species counts (Table G-1), a heatmap of companion crop biomass (Figure G-1) highlight the greater establishment and growth of the companion crop following the control of phase 1. Photos of the companion crop are also given below.

Table G-1: Companion crop species counts per m^2 in the control and cover crop treatment

	Tall fescue	White clover
Control	40	4
Cover crop	12	0

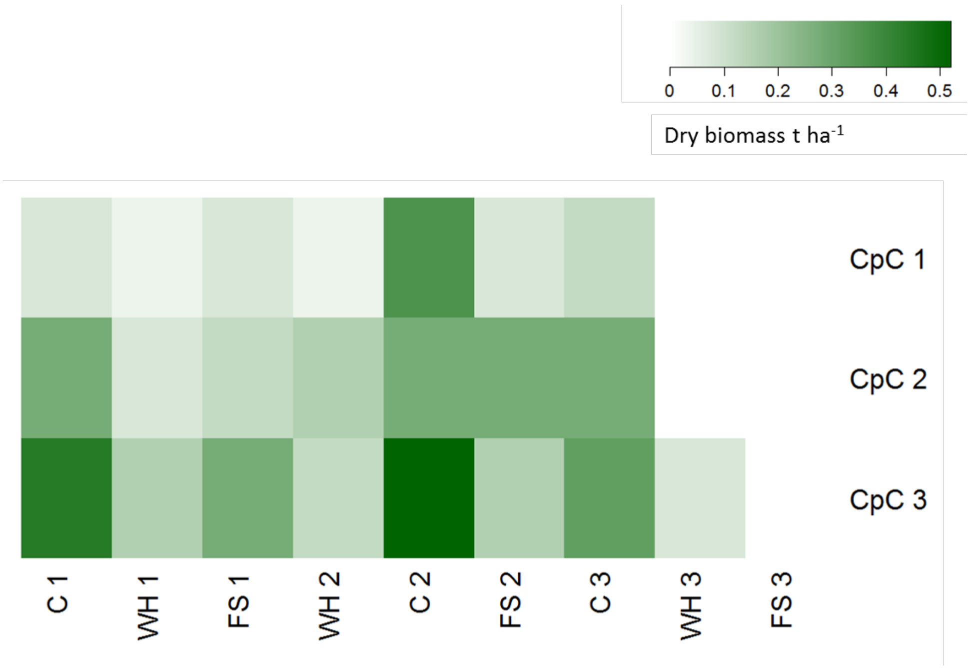


Figure G-1: Heatmap of Companion crop biomass (t ha^{-1}) across the trial plots

Figure G-2: Companion crop biomass taken 19th October 2017, 1 week after maize harvest. The foreground shows companion crop growth following the control of phase 1 whilst the back of the picture shows a more sparse population of companion crops which followed the CC treatment of phase 1

Figure G-3: Companion crop growth on 13th March 2018. Substantial damage from the herbivores over winter reduced the biomass of the companion crop

Figure G-4: Companion crop biomass on the 24th April 2018.

Appendix H Soil Available N Following Phase 2

Following phase 2, Prickwillow there was a significant reduction in soil available N ($p<0.05$) in the treatments which contained a companion crop (Table H-1) which can be attributed to the increase in biomass of the companion crop from mid-March onwards (Figure G-3, Figure G-4).

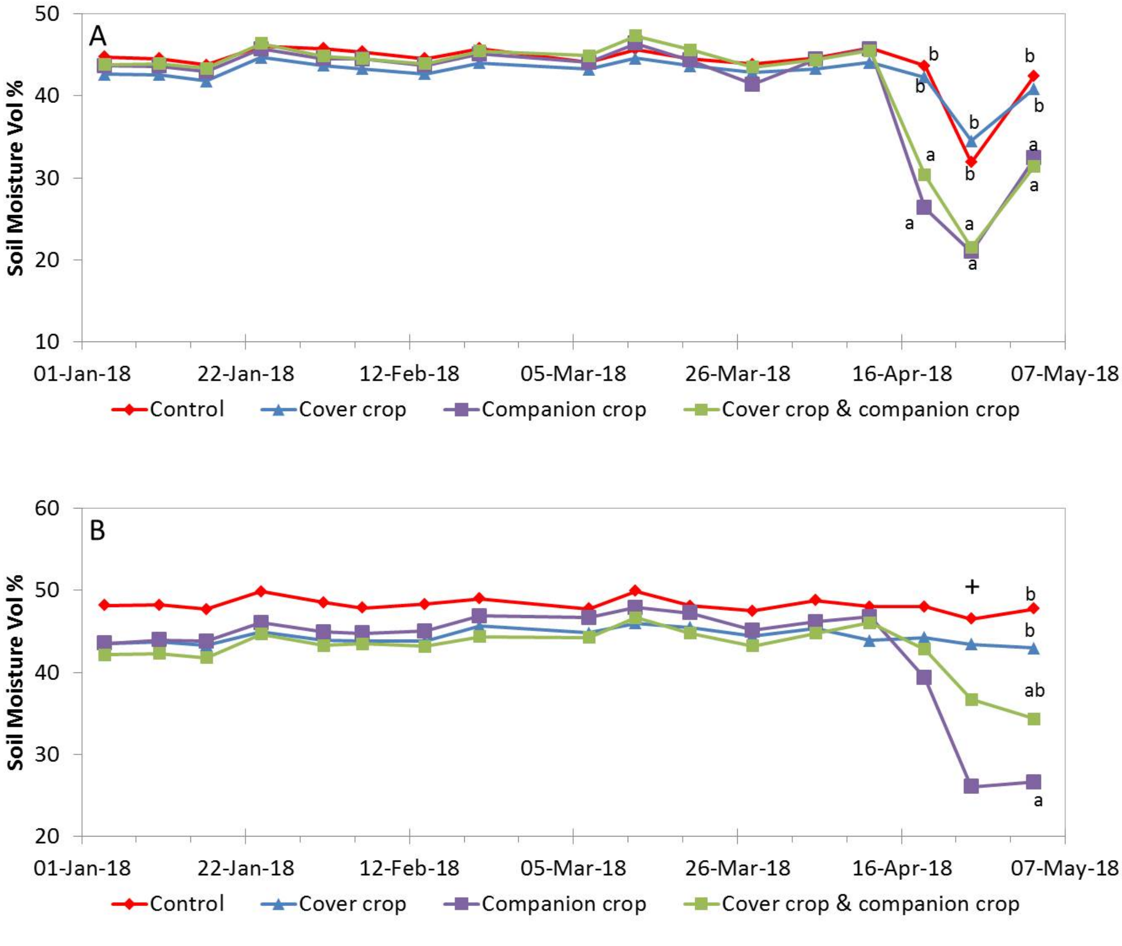
Table H-1: Soil available N (mg N kg^{-1} of soil) on 3rd May 2018, at the Prickwillow trial site following phase 2.

Trial site	Control (No cover or companion crop)	Cover Crop (No Companion crop)	Companion Crop (No cover crop)	Cover & Companion Crop
Prickwillow phase 2	8.60^{a} (0.18)	8.09^{a} (1.21)	2.05^{b} (0.17)	1.77^{b} (0.26)

Appendix I Soil Moisture During Phase 2

During phase 2, Prickwillow, weekly soil moisture measurements were taken using the PR2 probe (Delta T Devices, Burwell, UK). At depths 0.1, 0.2 and 0.3m companion crops significantly ($p<0.05$) reduced soil moisture from 19th April 2018 onwards when compared to the control of phase 2, which was bare soil. On the 25th April 2018 at 0.2m depth there was a statistical interaction between the main effects (CC and companion crop), thus Tukey HSD *post hoc* analysis was not undertaken.

A reduction in soil moisture following the companion crops in late April is due to the increased transpiration of the companion crop which has increased in biomass substantially from the 13th March 2018 (Figure G-3, Figure G-4) due to the improved growing conditions.



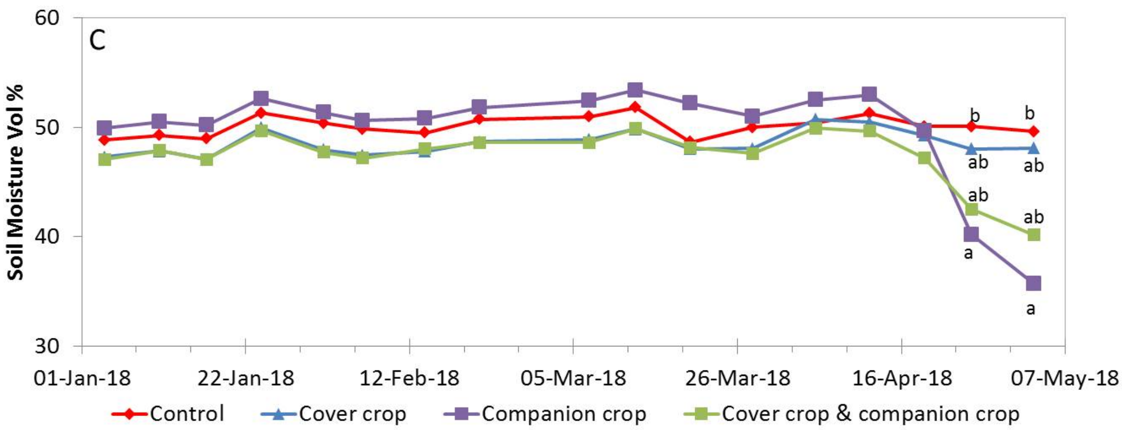


Figure I-1: Volumetric soil moisture (vol %) measured at 0.1m (A), 0.2m (B) and 0.3m (C) depth. Different letters within a date (vertical column) denote statistical difference (p<0.05) between treatments. The symbol '+' denotes a statistical interaction.

Appendix J Thesis Data

Data used in the thesis and subsequent publications can be found electronically using the links below:

Chapter 3: A U.K. survey of the use and management of cover crops

https://doi.org/10.17862/cranfield.rd.7314278

Chapter 4: Cover crops for timely nitrogen mineralisation and soil moisture management

https://doi.org/10.17862/cranfield.rd.7660817

Chapter 5: Limited effect of cover crops on soil structure in the short term

https://doi.org/10.17862/cranfield.rd.7946747

Chapter 6: The effect of cover crops on earthworm, microbial and fungal communities

https://doi.org/10.17862/cranfield.rd.7946783